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The use of regression analysis to characterize performance and properties of tungsten carbide cutting tools.

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THE USE OF REGRESSION ANALYSIS TO CHARACTERIZE PERFORMANCE AND PROPERTIES OF TUNGSTEN CARBIDE CUTTING TOOLS

by

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career. I hold the highest respect for his educational and guidance abilities, and the concern he shows his students is unequaled. Whatever success I have achieved, has been largely due to the inspiration provided by this man.

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ABSTRACT

The same seven experimental steel cutting grades of tungsten carbide prepared during a thesis done by William Scheithauer[1] were utilized in an attempt to further investigate the possibilities of correlating tool properties with performance. Flank and nose wear measurements for three distinct conditions, providing a wide range of tool operating temperatures, provided six dependent variables. Four elevated temperature measurements of thermal diffusivity were added to the thirteen properties collected by Scheithauer to provide seventeen independent variables. Stepwise linear regressions were run for all six dependent variables, and for four groups of data constructed from combinations of two replications made for each wear sample. Although very significant correlations were obtained for all 24 regressions, different equations were obtained depending upon the data group used, i.e., one general, and therefore, reliable, equation for each specific condition was not the result. In an effort to yield reliable predicting equations for all four data combinations, nine highly intercorrelated and/or room temperature measured properties were left out of the final regressions. The eight remaining properties produced similar results for all four data groups, giving

support to the regression's ability to be flexible and valid in predicting performance. The reliability obtained with the reduced independent variable matrix was yielded with minimal loss in correlation significance. All six final equations had correlations significant at the 90% confidence level; three were significant at the 99% level. Since the variables remaining out of the original seventeen were largely elevated temperature properties, support is, therefore, given to the idea that these properties are important in predicting performance. Collinearity was shown to be a problem in all regressions, and was reduced in the regressions run with the eight selected independent variables. Scatter plots were drawn for all independent versus the dependent variables, indicating a lack of linear relationships for almost all variables. The results closely paralled those of Scheithauer, showing the importance of properties seldom measured, especially elevated temperature properties, and that a good correlation of properties with performance is possible, even when using multiple linear regression to yield the predicting equations. Where collinearity did not cause positive or negative sign problems, physical significance could be easily attached to the independent property's indicated effect on the dependent variable.

INTRODUCTION AND OBJECTIVES

It should be noted at the outset that the idea for this thesis stems from two main inspirational sources. The first source consists of the problem as it exists, while the second source is comprised of one attempt to provide a feasible solution to the problem.

The problem referred to herein is the present systems used by carbide cutting tool manufacturers to aid in the proper selection of a carbide for any user's particular need in a cutting situation. Anyone who has been faced with having to use any of the three main classification systems in use today (International Standards Organization, British Hard Metals Association, or Cemented Carbide Producers Association) quickly realizes the difficulty in selecting a particular grade for proper optimal application to some cutting situation, with only the type of information provided by any of the systems. The difficulty arises when the user is forced to use highly qualitative information about the tool and/or cutting situation, to make a decision about a highly quantitative cutting situation.

The second inspirational source mentioned above was a recent attempt to a start of a solution to the problem described above. Considerably good results were produced in a thesis written by William Scheithauer, Jr. during the Lehigh academic year 1974 - 1975. His thesis, entitled "A Characterization of the Performance and Properties of Cemented Carbide Cutting Tools", yielded excellent results in correlating measurable quantitative physical properties, of the seven carbides tested, to quantitative performance properties of actual cutting tests.[1] Scheithauer's efforts were, for the most part, devoted to the measuring and collection of a wide array of physical and mechanical properties for each of the seven different carbide grades tested. Thus a somewhat narrower scope of performance testing was necessitated. The basic research was successful though, in that it proved that a high correlation between quantitative physical properties and quantitative performance properties does exist, at least for the conditions considered by Scheithauer. It also indicated that a few select properties alone are effective in predicting performance. It is important to note that the results showed that the certain few select properties were, in most cases, not the ones now given to the user by the manufacturer to be used as informative indicators.

The research presented within this thesis was felt to be necessitated by:

(1) the continuing dilemma faced by the expert

or novice carbide user when trying to produce optimal cutting situations via the correct choice of grade of tool material from the ever growing array of products made available by all carbide manufacturers, and by

(2) the initial signs of success toward a feasible solution to the problem produced by Scheithauer.

It seemed apparent after the results by Scheithauer were studied, that a much wider array of performance data should be collected and subjected to regression techniques to investigate the effects of different cutting situations upon the results produced by regression. Also, any other physical properties which could be collected should be added to Scheithauer's initial matrix to search for better indicators of performance.

A third factor contributing to the inspiration for this work was the author's desire to continue the efforts of so many people who are involved in trying to determine a more scientific approach for the design, and subsequent use of tungsten carbide cutting tools.

In summary, the work described herein involves efforts to accomplish the following objectives:

(1) to characterize different physical properties of the seven experimental alloys to add to the matrix already produced by Scheithauer,

(2) to characterize the cutting performance of the seven tool alloys by utilizing a series of cutting conditions which will

subject the tool alloys to a much wider, and more representative range of the variables present in cutting situations, especially temperature,

(3) to determine the extent and significance to which a correlation exists between the now expanded matrices of properties and performance for the seven alloys,

(4) to investigate any problems resulting from the use of multiple linear regression equations to define the relationship between the tools' properties and performance, and

(5) as a fifth, and secondary objective relative to the first four, to review qualitatively the regressions' implied effects of the tools' properties on performance.

The results produced by this research will hopefully contribute information as to which measurable properties are most important, and in what amounts, towards predicting performance values. It will also extensively investigate the use of regression techniques to define the supposed relationships. The final results will hopefully be useful in providing more needed framework towards alternative methods in classification systems for tungsten carbides so that better manufacturer classification, and hence, better user application can be affected. Also, the results may provide useful insight towards which properties should be used as indicators in research for better performing tungsten carbide cutting tools.

BACKGROUND INFORMATION

Definition of the Problem and Previous Work

One must have nothing less than compassion for all the tool engineers, foremen, machinists, etc. who are faced with having to make tungsten carbide grade selections from the continuously growing, and certainly complex array of available carbide cutting tools. Anyone familiar with the dilemma soon realizes that the chances of choosing the grade most likely to result in the realization of an optimal, or minimum cost cutting situation, are disturbingly low. In fact, while hopefully not true, it usually appears to the carbide user that the manufacturers are making a sincere attempt to confuse everyone.[2]

The problem stems from the lack of a simple, or even a complex, infallible algorithm which would define the exact choice of grade for all situations. Thus the user is invariably faced with trial and error selection. Most materials intended for a required application can be evaluated by comparing inherent physical properties with data documented on the correlation of certain physically important properties with the performance criteria desired. The situation is not nearly so clearly defined when it comes to tungsten carbides used as cutting tool materials.

It is true that tungsten carbides are classified by three predominantly used systems, but none of them allow straightforward selection of a tool for end use. Both the American C system and the International Standards Organization system attempt to classify carbides according to application, i.e., type of material to be cut, and type of cut. The ISO system, though, is somewhat more explicit in that it classifies tools according to specific work materials and specific cutting conditions, while the C system uses a much more general array of catagories. The third system,offered by British Hard Metals Association (BHMA), classifies carbides by three tool characteristics: wear resistance, shock resistance, and crater resistance. Thus, by the inherent nature of all three systems, they only give users a very rough idea of an appropriate selection for any one case.

One problem in the above mentioned systems is that the manufacturer, not the user, is charged with placing his particular tool materials into the proper classification catagory. This fact, along with the unspecific dividing lines between catagories for all three systems,causes what the user might call "erroneous classification of carbides by the manufacturers". Generally, the user cannot then assume that all carbides placed into the same classification slot will perform equally well. This current dilemma was especially well proved by McTamany and Kane.[3,4] They showed that when manufacturers were allowed to submit candidate carbides for performance evaluation, when given specific cutting applications, grades from many different classification slots were submitted. Subsequent performance evaluation then showed a wide range of results, pointing out the manufacturers' own inabilities to properly select carbides for use with the current systems, and/or showing their inabilities to classify them accurately in the first place.

One naturally begins to wonder why tungsten carbides cannot be so easily classified and applied to actual cutting situations. As mentioned previously, other materials, such as metals, can usually be selected by simple review of critical material properties which are selected on the basis of existing data correlating the properties with the required performance. Such data does not exist for carbide selection; possibly only due to the lack of attempts to do so. Another problem might be that it is not clear which properties are important in defining performance. Manufacturers tend to measure only those properties which are inherently easier to measure, or those properties which are able to aid them in quality control of carbide batches. Consequently most of the properties measured are taken at ambient room temperature. It cannot be assumed that if one carbide has a higher property value than another at ambient, the relationship will be preserved at higher temperatures.[5] Thus room temperature properties used as a criteria for selection can be very misleading. Ironically, it has been rather well documented that cutting tools usually operate well above ambient.[6] It therefore must make one suspect that high temperature properties might play a role in performance.

Quite a few studies have been done on trying to determine those process variables which affect certain basic properties of tungsten carbides.[7,8,9] Also, many studies have been successful in determining qualitative descriptions of tool performance based on tool properties.[2,10,11,12] Some researchers have even attempted semi-quantitative studies trying to relate properties and performance.[13,14,15] By far the most promising work the author has seen to date was produced by William Scheithauer in 1974.[1] His thesis was successful in quantitatively relating a series of measured properties to certain cutting performance results, with the use of multiple linear regression. It is exactly this work that the author tends to pursue within this thesis, further attempting to examine the possibility of quantitatively relating properties to performance.

Preparation of Experimental Alloys

The alloys used in this study were provided by William Scheithauer, Jr. from the same group of alloys used by him in 1974.[1] It must be noted that the availability of the same alloys was paramount to the conception of this thesis. Much work was done by Scheithauer in collecting the property measurements for all seven alloys used herein, allowing the continuation and expansion of the work he began without duplication of effort.

The alloys obtained for this study were prepared by Walmet Cemented Carbides, Detroit, Michigan. All seven are experimental steel cutting grades, initially designed to cover a range of three variables in the production of the final carbide produced. Table I lists the target compositions and variables selected to affect the final carbide properties. Variables chosen to alter properties, and hopefully, performance, were:

(1) WC powder particle size,

(2) amount of TaC, and

(3) the method of making TaC addition.

The exact description of the preparation method for the alloys is not reproduced here, but can be found in Scheithauer's work.[1] For easier reference, Table II

TABLE I

PROPOSED ALLOY COMPOSITIONS AND VARIABLES

ALLOY CODE	WC w/o	TiC w/o	TaC w/o	Co w/o	QUALITATIVE GRAIN SIZE OF WC
A	72.0	8.0 (1)	11.5 (2)	8.5	fine
B	72.0	8.0 (1)	11.5 (2)	8.5	medium
C	72.0	8.0 (1)	11.5 (2)	8.5	coarse
D	76.0	8.0 (1)	7.5 (2)	8.5	medium
E	80.0	8.0 (1)	3.5 (2)	8.5	medium
F	76.0	8.0 (3)	7.5 (3)	8.5	medium
G	80.0	8.0 (4)	3.5 (4)	8.5	medium

(1) TiC added as 50/50 WTiC

(2) TaC added as TaC

(3) Added as 50/25.81/24.19 WTiTac (Solid Solution)

(4) Added as 50/34.79/15.21 WTiTaC (Solid Solution)

is reproduced here to show the final analysis of the experimental alloys.

TABLE II

CHEMICAL ANALYSIS OF EXPERIMENTAL ALLOYS

ALLOY CODE	WC w/o	TiC w/o	TaC w/o	Co w/o
A	73.4	7.8	10.4	8.5
B	73.1	7.9	10.6	8.6
C	73.4	8.2	10.9	8.4
D	77.0	7.9	6.9	8.7
E	81.6	8.1	3.0	8.1
F	75.4	7.9	7.0	8.8
G	80.6	7.9	3.0	8.0

DESIGN OF EXPERIMENT

The research herein is designed to be a follow up of Scheithauer's look at the widest application of tungsten carbide cutting tools: the rough turning of steel. Unbound by the necessity of having to spend large amounts of time in measuring a number of physical properties for each of the seven alloys tested, a greater proportion of time will be spent in collection of new performance data, and then in the subsequent analyzation of results for correlation between properties and performance. Aided by the insight provided by others, especially Scheithauer, the direction taken by this thesis should hopefully prove even more fruitful towards providing needed conclusions in the relatively untouched field of trying to quantitatively relate properties and performance of tungsten carbide cutting tools.

Independent Variables

The following were selected as independent variables:

FACTOR	LEVEL	IDENTIFICATION OF LEVELS
Tool Materials	7	Alloys A,B,C,D,E,F, and G
Tool Properties	17	See Table III
Work Material	1	Hot Rolled SAE 1045 at R_g 70
Speeds, SMPM	3	30.48,60.96, and 121.92
Repetitions	2	Replicate One, and Replicate Two

All other process variables are held constant, i.e., feed, depth of cut, cutting time, type of cut, geometry, etc. are not varied at all. The first thirteen of the total seventeen properties were obtained directly from Scheithauer.[1] The last four are all thermal diffusivity measurements made at elevated temperatures. These four measurements were made on all seven tool alloys at facilities provided at the Materials Research Center of Lehigh University. Being that it is well known that cutting tools operate at well above room temperatures, it seems intuitively obvious that this property, especially when measured at elevated temperatures approaching those present in actual cutting, might possibly provide a good correlation with performance.

The seventeen properties listed in Table III combine commonly measured properties by the manufacturers, almost always at room temperature (298°K), with more

TABLE III

PROPERTIES MEASURED ON EXPERIMENTAL ALLOYS

1. Apparent Grain Size, μm.
2. Density, gm/cm^3.
3. Coercive force, Oe.
4. Hardness:
    (a) DPH at room temperature (298.15°K), (25°C).
    (b) R_a at room temperature (298.15°K), (25°C).
    (c) Vickers at room temp. (298.15°K), (25°C).
    (d) Vickers at 673.15°K, (400°C).
    (e) Vickers at 1073.15°K, (800°C).
5. Transverse Rupture Strength, GN/m^2 at room temperature (298.15°K), (25°C).
6. Abrasion Resistance at room temperature (298.15°K), (25°C).
7. Fracture Toughness, $MN/m^2 - m^{1/2}$.
    (a) At room temperature (298.15°K), (25°C).
    (b) At 673.15°K, (400°C).
    (c) At 1073.15°K, (800°C).
8. Thermal Diffusivity, mm^2/sec.
    (a) At 473.15°K, (200°C).
    (b) At 673.15°K, (400°C).
    (c) At 873.15°K, (600°C).
    (d) At 1073.15°K, (800°C).

physical property measurements not usually taken by any manufacturers. It can be seen that the uncommonly measured properties listed are, for the most part, taken at elevated temperatures. All measurements are made according to the manufacturers' generally accepted procedures.[16] The inclusion of property measurements taken at elevated temperatures stems from the author's suspicion of a higher correlation between these properties and performance. It seems only natural to compare carbides based on property measurements taken at, or near the same temperatures at which the tool operates. As already mentioned, comparisons made with room temperature properties can sometimes lead to erroneous judgements.[5]

The selection of the cutting conditions was based completely on the attempt to produce a wide range of temperatures at the tool tip. While Scheithauer was concerned with interupted vs. continuous cutting, etc., his cutting conditions never reflected a situation where higher speeds were considered to yield higher temperatures. Thus, this work will be completely concerned with producing a range of temperatures which hopefully present the comparable range of temperatures possible in most cutting situations. In this manner we might better be able to examine the relationship between the properties and the resulting performance values for a representatively wide range of tool operating temperatures.

Dependent Variables

In choosing a dependent variable, or variables, to be measured for the purposes described herein, one must strive to pick that performance variable which most closely defines tool performance, or tool life. Such variables as surface finish, cutting forces, thrust forces, flank wear, nose wear, and crater wear are the ones most often viewed as indicators of tool life. Because flank and nose wear were used by Scheithauer as the dependent variables, and because these variables are most often viewed as the most accepted, and easily measured variables in cutting situations, the same two parameters will be used here as the dependent variables defining tool performance.[1] The mechanisms of wear have been sufficiently documented elsewhere, and thus, will not be discussed here. It is also felt that flank and nose wear would be primarily dependent on tool properties, therefore providing the type of relationship needed to investigate possibilities of correlation between independent and dependent variables.

Thus, the dependent variables measured were:

(1) flank wear, and

(2) nose wear.

Equipment and Instrumentation

The equipment and instrumentation described at this point pertain only to the performance characterization phase of this research. The first thirteen physical properties listed in Table III were measured during the work of Scheithauer, hence, the interested reader may find the specific procedures and methods of measurement used to complete that phase contained within that thesis.[1] The last four physical properties listed in Table III, i.e. the thermal diffusivity values at four elevated temperatures, were made during the scope of this thesis, but the discussion pertaining to the attainment of these values will be postponed at this point.

The performance characterization of the seven alloys was made completely with equipment contained in the Manufacturing Processes Laboratory at Lehigh University, and under the direction of Professor George E. Kane, Director. The following is a complete list of all equipment used:

(1) Lathe - Lodge and Shipley 20 horsepower engine lathe with a 20" swing, and a 54" center to center distance. A rheostat control is provided to allow the operator to maintain desired surface speed settings.

(2) Tachometer - A Jagabi hand held tachometer was used to measure the surface speed of the workpiece to insure that exact speeds were always maintained. The measuring range of this instrument was 0 to 500 surface feet per minute.

(3) Toolmaker's Microscope - A Bausch and Lomb toolmaker's microscope was used for all flank and nose wear measurements. Previous studies indicated that the accuracy of this instrument was ± 0.001".[17]

Experimental Procedure

All experimental methods description related here will pertain only to the performance characterization phase of the research. The main experimental parameters are listed in Table IV.

All cutting was done as rough turning on AISI 1045 steel supplied by Bethlehem Steel Corporation. The steel was received as hot rolled, with dimensions equal to 8" in diameter, and cut into 48" lengths. Nowhere was a cutting fluid ever used, either as a lubricant, or as a coolant. All three cutting conditions employed the same depth of 2.54 mm.(.100"), the same feed equal to

TABLE IV

CUTTING CONDITIONS FOR PERFORMANCE CHARACTERIZATION

	Condition Number		
	ONE	TWO	THREE
Speed, SMPM(SFPM)	30.48(100)	60.96(200)	121.92(400)

CONDITIONS CONSTANT FOR EACH CUT

Feed, mmpr(ipr)	- .795 mm./rev.(.0313 in./rev.)
Depth of cut, mm.(in.)	- 2.54(.100)
Type of Cut	- Continuous
Cutting Time	- 9 minutes
Insert Style	- SNG-633
Operation	- Rough Turning
Workpiece Material	- Hot Rolled 1045 steel (R_g-70)
Coolant or Lubricant	- None
Net Cutting Geometry	- -5°,-5°,5°,5°,15°,15°,3/64 in.

.795 mm./revolution (0.0313 ipr), and an always constant depth, continuous cut was utilized.

Prior to experimental cutting with the seven alloys, all steel bars were subjected to a clean up cut to remove all dirt and mill scale. This typically resulted in a diameter reduction of from 20.32 cm. (8") to 19.05 cm. (7.5"). The tailstock end of the workpiece was always chamferred to 15°, conforming to the side cutting edge of the tool alloys. This was done to minimize cyclical shocks which can occur when the tool initially enters the workpiece from either end.

The net cutting geometry, i.e. the geometry obtained with the insert locked into the tool holder, and with holder mounted on the tool post, is listed in Table IV.

All alloys were provided with all surfaces ground, no hone on any edges, and were manufactured into the style known as SNG-633.

Hardness values were taken for the 1045 steel used for the work material. Fortunately, the hardness values taken across the diameter were almost constant. Thus the work material had almost equal hardness for all cuts, no matter what the diameter of the workpiece at that point. The choice of 1045 for the work material was made on the basis of total amounts sold to consumers, and on the basis of which materials were available in the lab in sufficient quantities. Because 1045 is a widely used steel, and because the rest of the highly used 1000 series of low carbon steel alloys would probably react similarly, it was felt that 1045 would make an appropriate candidate material for this research.

For all cutting required by the performance characterization, the following steps were adhered to:

(1) The feed setting was first made while all clutches were disengaged.

(2) The speed setting was made and the spindle clutch was engaged. The speed was then checked with a tachometer and readjusted if necessary.

(3) The tool was zeroed on the workpiece with the bar in motion, and then the proper depth of cut was set.

(4) The feed clutch was engaged.

(5) Time was measured starting when the tool started cutting, and ending after nine minutes of cutting when the feed clutch was disengaged and the tool backed simultaneously out of the workpiece.

(6) The insert was then removed from the mechanical holder and placed under the toolmaker's microscope. The flank wear, and the nose wear were then measured and recorded.

(7) Each of the three conditions, for each of the seven alloys, was repeated a second time. The procedure for the second repetition was exactly the same as before, except that the order of running the alloys was reversed.

(8) After both cuts were done for each condi-

> tion, from here on referred to as replicates one and two, a total of six independent readings were taken for each wear result. Independent implies that readings were always made without the review of prior results. Six readings were made to reduce the reading error, especially for condition three, which resulted in relatively high amounts of flank and nose wear.

The complete record of the cutting results is shown in Appendix B.

RESULTS AND ANALYSES

This section will be subdivided into three parts; property characterization, performance characterization, and correlation of properties and performance.

Property Characterization

Tables V,VI,VII, and VIII are reprinted listings of the property measurements, performed by Scheithauer, for each of the seven alloys. Table V lists the values obtained for grain size, density, coercive force, Diamond Pyramid Hardness (DPH), and Rockwell A hardness (R_a). Table VI contains Vickers hardness measurements made at room temperature (298.15°K), at 673.15°K, and also at 1073.15°K. Transverse rupture strength (TRS) and abrasion factor measurements are shown in Table VII. Fracture toughness values at room temperature (298.15°K), 673.15°K, and at 1073.15°K are listed in Table VIII.

These properties comprise the first thirteen, out of seventeen, different types of values considered for possible correlation with performance during the course of this work.

TABLE V

GRAIN SIZE, DENSITY, COERCIVE FORCE, AND HARDNESS MEASUREMENTS OF EXPERIMENTAL ALLOYS

ALLOY CODE	GRAIN SIZE, μm	DENSITY, gm/cm^3	COERCIVE FORCE, Oe	HARDNESS(1) DPH	R_a
A	1.43	12.55	154.	1520.	92.0
B	1.74	12.49	121.	1503.	91.3
C	1.60	12.47	119.	1442.	91.2
D	1.98	12.50	115.	1464.	91.2
E	1.70	12.61	118.	1443.	91.4
F	1.63	12.56	119.	1439.	91.5
G	1.82	12.59	113.	1410.	91.3

(1) Measured at room temperature ∿ 298.15 °K (25°C)

TABLE VI

VICKER'S HARDNESS MEASUREMENTS

ALLOY CODE	TEMPERATURE, °K (°C)		
	298.15(25)	673.15(400)	1073.15(800)
A	1560.	1017.	790.
B	1500.	967.	775.
C	1469.	908.	760.
D	1439.	997.	766.
E	1463.	975.	763.
F	1494.	917.	733.
G	1494.	1003.	734.

TABLE VII

TRANSVERSE RUPTURE STRENGTH AND ABRASION FACTOR

ALLOY CODE	TRS, GN/m^2 (KSI)	ABRASION[1] FACTOR
A	1.471 (213.4)	21.5
B	1.391 (201.7)	22.5
C	1.848 (268.0)	26.2
D	1.447 (209.9)	24.5
E	1.242 (180.1)	26.5
F	1.377 (199.7)	22.1
G	1.575 (228.5)	25.0

(1) Abrasion factor is dimensionless; the smaller the factor, the better the abrasion resistance.

TABLE VIII

FRACTURE TOUGHNESS OF EXPERIMENTAL ALLOYS

ALLOY CODE	FRACTURE TOUGHNESS (K_{1C}) IN $MN/m^2 - m^{1/2}$, ($KSI - in^{1/2}$) AT SPECIFIED TEMPERATURE		
	298.15°K(25°C)	673.15°K(400°C)	1073.15°K(800°C)
A	45.01(40.96)	17.42(15.85)	13.33(12.13)
B	43.40(39.50)	15.52(14.12)	12.32(11.21)
C	43.68(39.75)	18.62(16.95)	12.91(11.75)
D	38.77(35.28)	15.50(14.11)	12.80(11.65)
E	38.69(35.21)	15.75(14.33)	12.00(10.92)
F	32.66(29.72)	15.16(13.80)	12.70(11.56)
G	33.96(30.91)	15.81(14.39)	11.00(10.01)

The last four of the seventeen independent property measurements considered for correlation were attained within the scope of this research. Coupled with the three conditions determining performance characterization values listed in Table IV, which were designed to provide a wide range of operating temperatures at the tool tip, the addition of thermal diffusivity measurements was felt to be likely to reveal good correlation with performance.

Thermal diffusivity is a property comprised of thermal conductivity (k), specific heat (c), and density (ρ). The relationship of these three defining properties to thermal diffusivity is:

$$\text{thermal diffusivity} = \frac{k}{(c) \times (\rho)}$$

Thermal diffusivity, then, is a property which defines the ability of a substance to diffuse heat, usually given as a rate of m^2/second. It is well documented that over 95% of the work done during cutting exhibits itself as heat.[6] Since this heat invariably reaches the tool, it seems likely that thermal diffusivity might be important in defining performance, especially where high temperatures are present at the tool. Intuitively, it initially seems that the higher the thermal diffusivity value for a tool, the better that tool is able to immediately diffuse the generated heat to the surrounding materials. If the tool can quickly diffuse the heat, generated at the tip, to the remaining tool material, the tool holder, the tool post, etc., the equilibrium temperature at the tip might be reduced. Since it is well known that higher tool temperatures can lead to a faster rate of deteriorization of the tool, via the theories of plastic deformation, diffusion, etc., a lower tip operating temperature might aid in lowering wear rates, assuming all other variables remain constant.[18,19,20] It should be noted that the thermal diffusivity measurements utilized in the correlation of properties with performance are all taken at elevated temperatures.

The data attained for the thermal diffusivity of each alloy was provided by the Materials Research Center of Lehigh University, under the direction of Dr. D. P. Hasselman. An experimental setup was used to maintain each specimen's temperature at many random points, while a laser flash technique would then evaluate the thermal diffusivity for a specific equilibrium temperature.

It was decided that thermal diffusivity values at 473.15°K, 673.15°K, 873.15°K, and at 1073.15°K for each alloy would be included in the properties matrix. Thus, the range of temperature used in determining thermal diffusivity vs. specimen temperature was, approximately, 473°K (200°C) to 1073°K (800°C). Due to the inaccuracy of the technique used in determining the thermal diffusivities, reliable measurements could not only be made at the four points required. Therefore, 42 points of data were taken for each alloy, in order that a representative curve might be yielded. The raw data results from the thermal diffusivity technique are completely listed in Appendix A.

With the aid of the LEAPS statistical package[21], and Lehigh University's Computing Center, initial scatter plots were drawn for each alloy showing thermal diffusivity vs. temperature. After close examination of all plots, it was determined that second degree equations would be developed to provide the best fit to the data. Second degree equations would also result in curves which closely match thermal diffusivity vs. temperature curves for other materials of similar nature.

After throwing out a few points which were obviously out of control, polynomial regressions were run for each of the seven alloys. The results of these regressions for alloys A,B,C,D,E,F, and G are shown in Tables IX,X,XI,XII, XIII,XIV, and XV respectively. Also included as Figures 1,2,3,4,5,6, and 7 are the polynomial regressions' calculated curves through the data points for alloys A,B, C,D,E,F, and G respectively.

Tables IX, X,XI, XII, XIII, XIV, and XV show the equation form, the coefficients, the standard error of the coefficients, the multiple correlation, the standard error of the regression, and the F statistics for each of the alloys. The correlations were significant at the 95% confidence level for all seven alloys, and also significant at the 99% confidence level for all but one alloy.

The equation resulted from each of the regressions was then used to calculate the thermal diffusivities for the seven alloys at 473.15°K, 673.15°K, 873.15°K, and at 1073.15°K. These calculated values are listed in Table XVI.

TABLE IX

THERMAL DIFFUSIVITY CURVE FITTING WITH POLYNOMIAL REGRESSION - ALLOY A

$$Y_A = b_0 + a_1(X^1) + a_2(X^2)$$

Y_A = Thermal Diffusivity, m^2/sec

X = Temperature, °K

b, a	COEFFICIENT	STANDARD ERROR
b_0	1.2556×10^{-5}	--------------
a_1	-6.4830×10^{-9}	2.3111×10^{-9}
a_2	1.6232×10^{-12}	1.4328×10^{-12}

Multiple Correlation = .9417

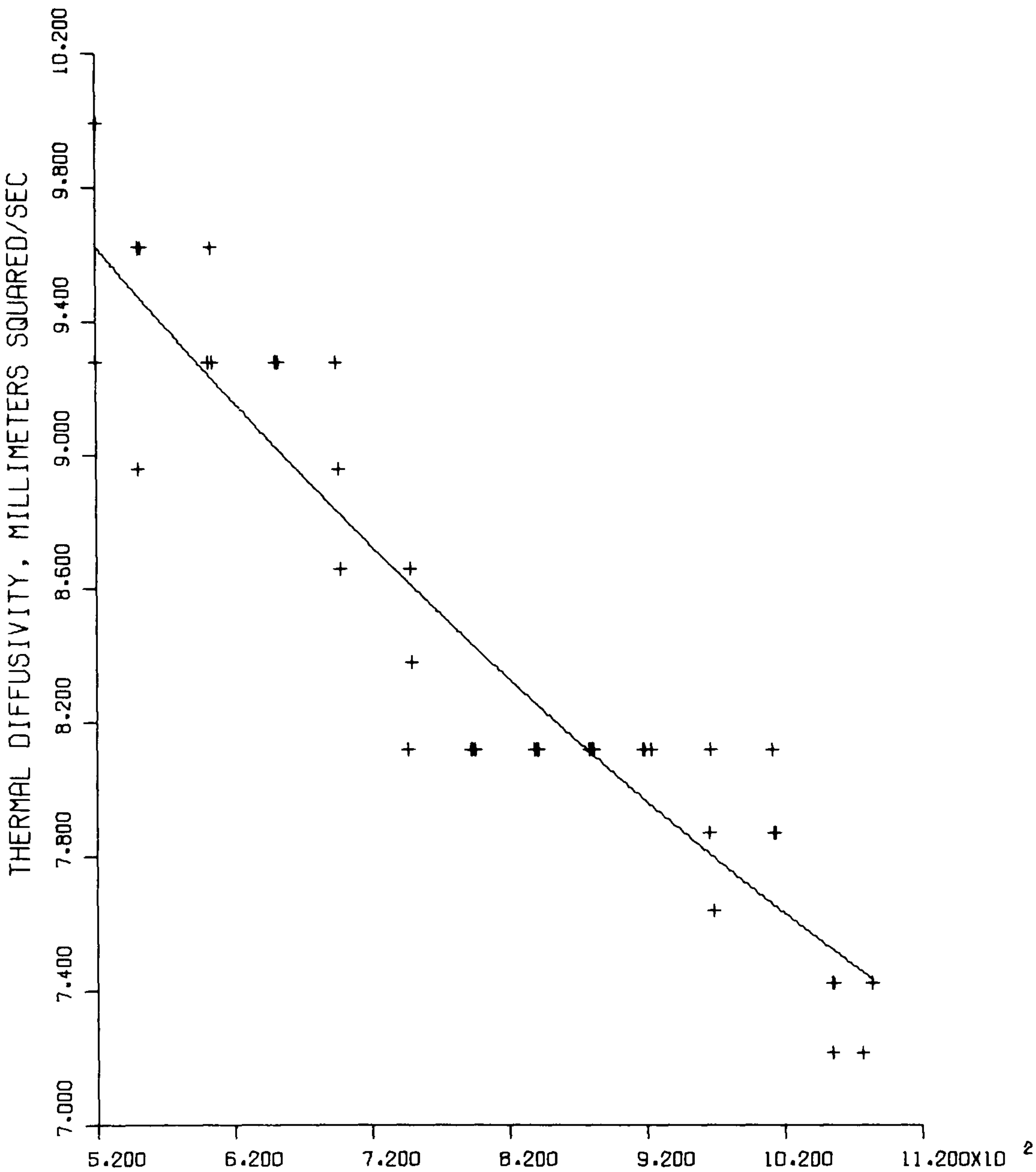
Std. Error of Estimate = 2.5916×10^{-7}

F statistic of regression = 152.75

F - Critical = 3.23

$\nu_1 = 2$, $\nu_2 = 32$, $\alpha = 0.05$

FIGURE 1



ALLOY A - T. D. VS. TEMPERATURE

TABLE X

THERMAL DIFFUSIVITY CURVE FITTING WITH POLYNOMIAL REGRESSION - ALLOY B

$$Y_B = b_0 + a_1(X^1) + a_2(X^2)$$

Y_B = Thermal Diffusivity, m^2/sec

X = Temperature, °K

b, a	COEFFICIENT	STANDARD ERROR
b_0	1.0760×10^{-5}	--------------
a_1	-4.0946×10^{-9}	2.7143×10^{-9}
a_2	6.7059×10^{-13}	1.7095×10^{-12}

Multiple Correlation = .8859

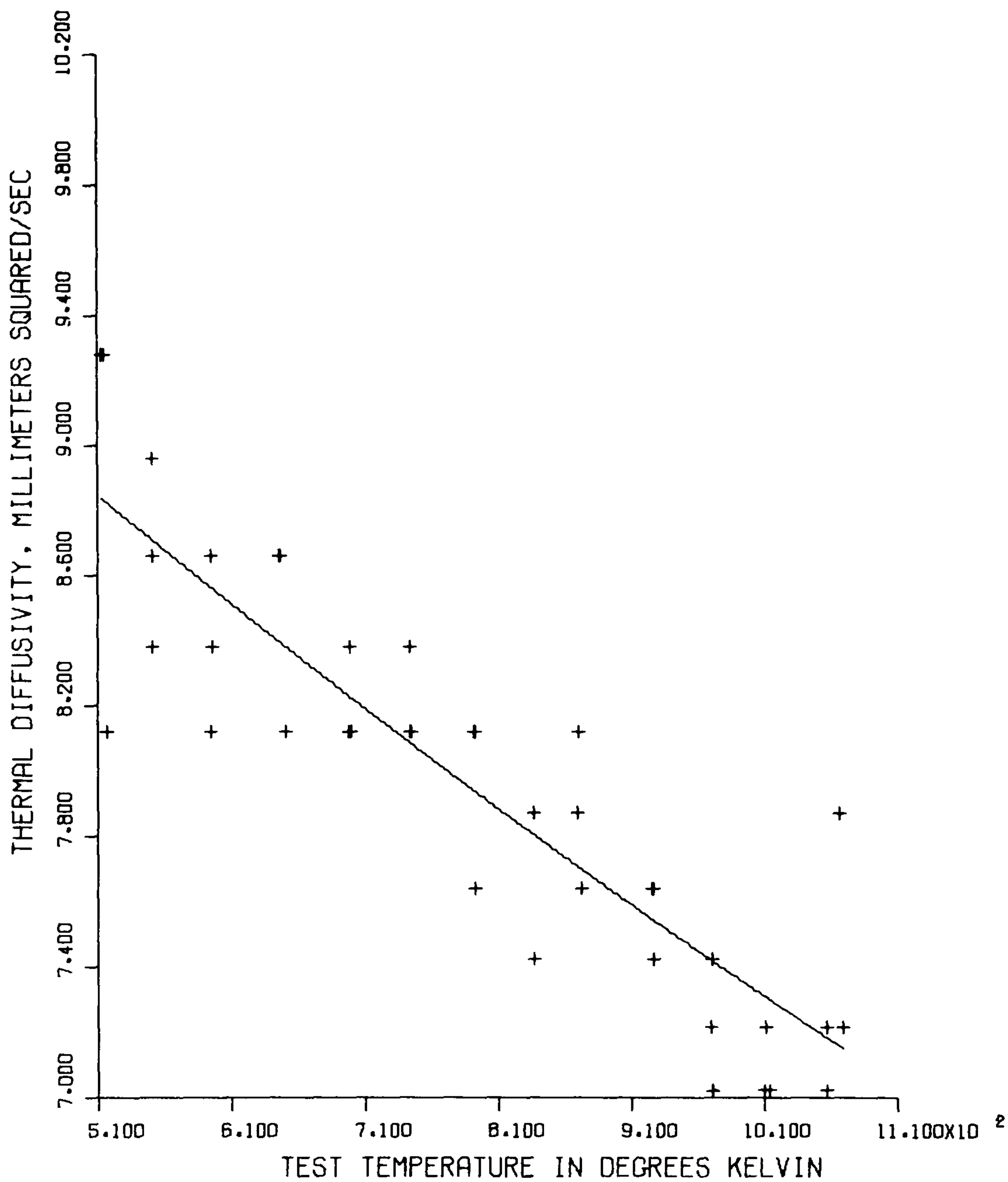
Std. Error of Estimate = 2.8965×10^{-7}

F statistic of regression = 67.48

F - Critical = 3.23

$\nu_1 = 2$, $\nu_2 = 37$, $\alpha = 0.05$

FIGURE 2



ALLOY B - T. D. VS. TEMPERATURE

TABLE XI

THERMAL DIFFUSIVITY CURVE FITTING

WITH POLYNOMIAL REGRESSION - ALLOY C

$$Y_C = b_0 + a_1(X^1) + a_2(X^2)$$

Y_C = Thermal Diffusivity, m^2/sec

X = Temperature, °K

b, a	COEFFICIENT	STANDARD ERROR
b_0	9.7885×10^{-6}	--------------
a_1	-1.1057×10^{-9}	2.2358×10^{-9}
a_2	-1.0011×10^{-12}	1.3728×10^{-12}

Multiple Correlation = .9062

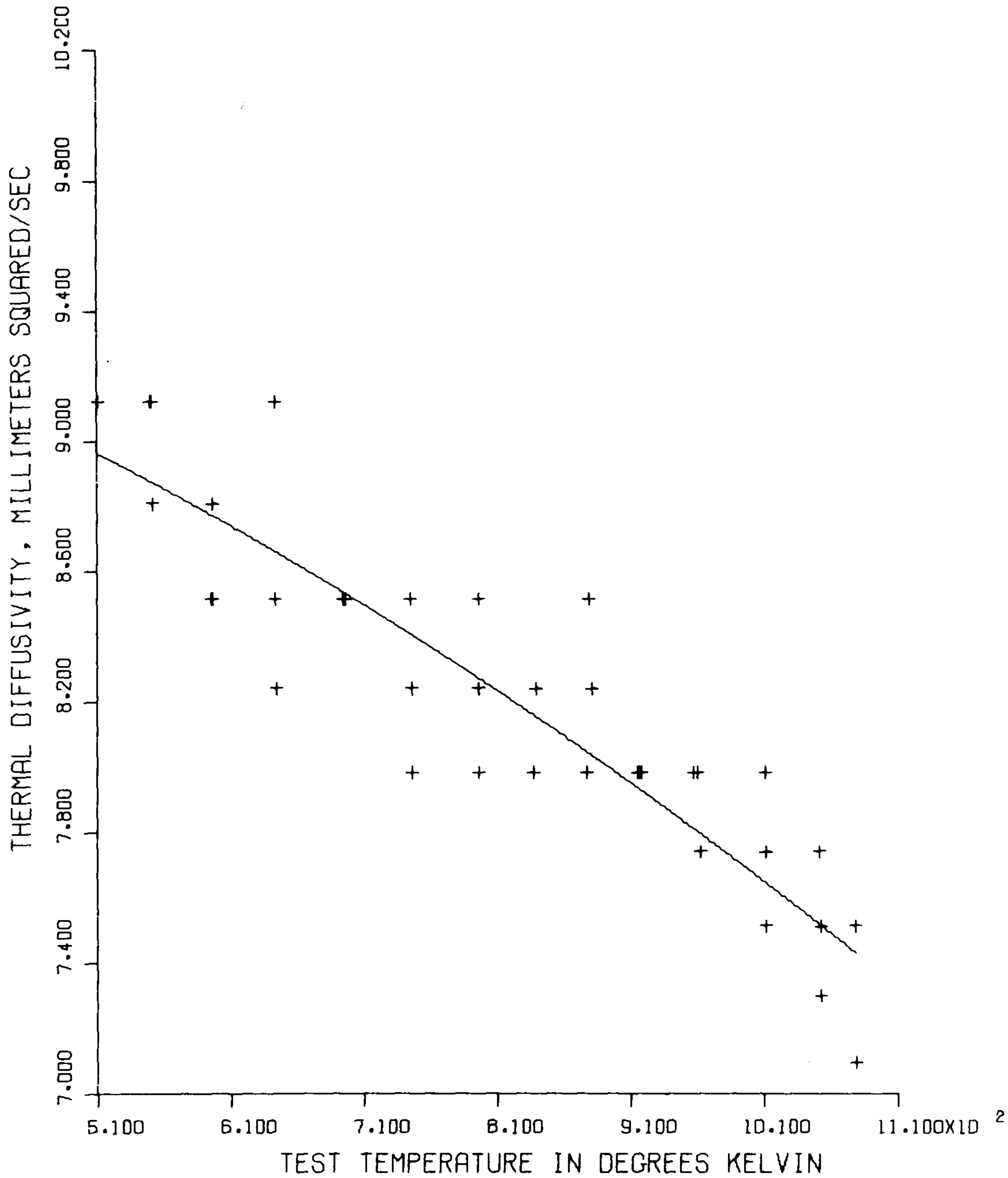
Std. Error of Estimate = 2.2898×10^{-7}

F statistic of regression = 84.96

F - critical = 3.23

$\nu_1 = 2$, $\nu_2 = 37$, $\alpha = 0.05$

FIGURE 3



ALLOY C - T. D. VS. TEMPERATURE

TABLE XII

THERMAL DIFFUSIVITY CURVE FITTING

WITH POLYNOMIAL REGRESSION - ALLOY D

$$Y_D = b_0 + a_1(X^1) + a_2(X^2)$$

Y_D = Thermal Diffusivity, m^2/sec

X = Temperature, °K

b, a	COEFFICIENT	STANDARD ERROR
b_0	1.2038×10^{-5}	--------------
a_1	-6.5124×10^{-9}	1.4472×10^{-9}
a_2	2.5046×10^{-12}	9.0304×10^{-13}

Multiple Correlation = .9463

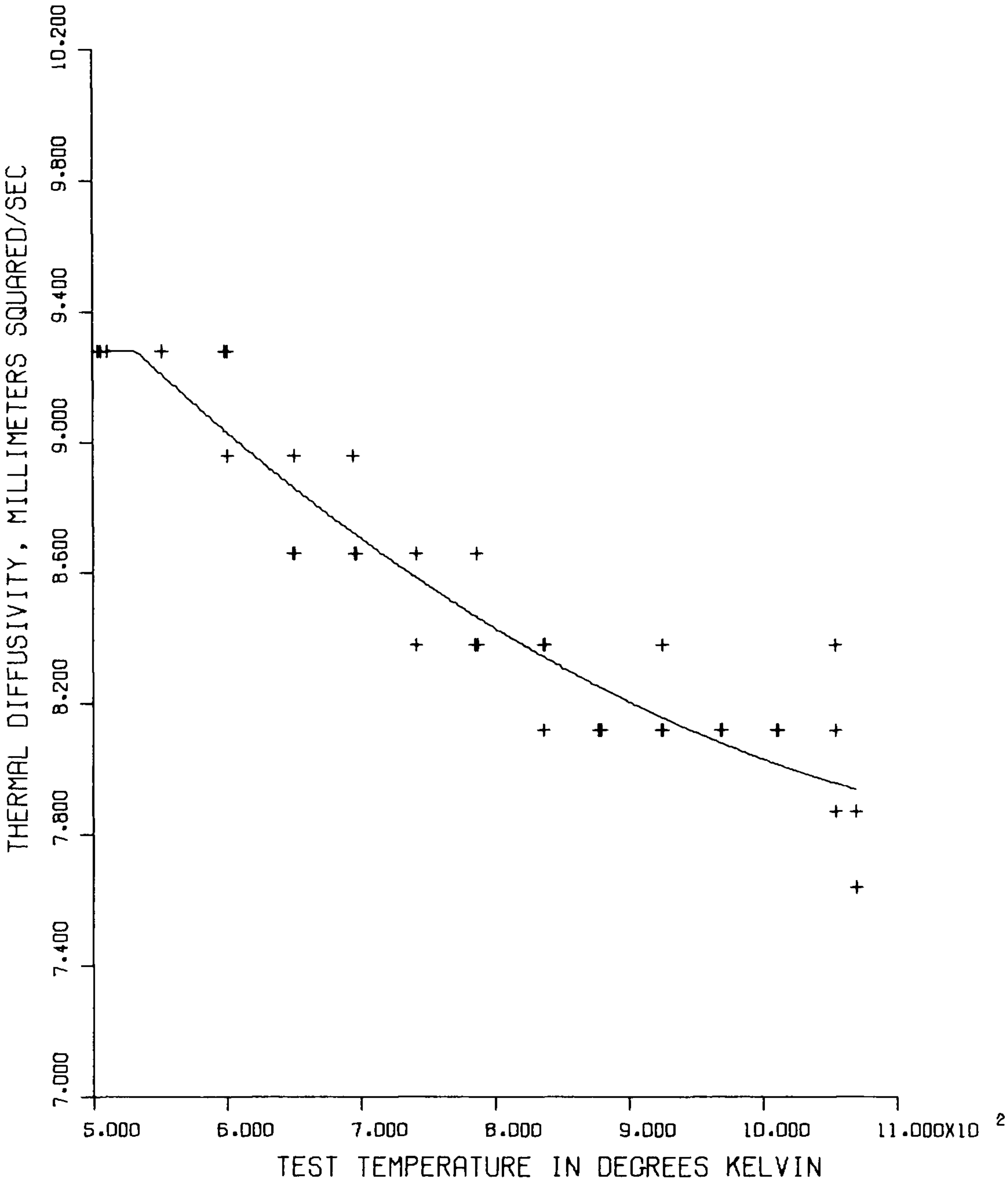
Std. Error of Estimate = 1.6392×10^{-7}

F statistic of regression = 162.73

F critical = 3.23

$\nu_1 = 2$, $\nu_2 = 38$, $\alpha = 0.05$

FIGURE 4



ALLOY D - T. D. VS. TEMPERATURE

TABLE XIII

THERMAL DIFFUSIVITY CURVE FITTING

WITH POLYNOMIAL REGRESSION - ALLOY E

$$Y_E = b_0 + a_1(X^1) + a_2(X^2)$$

Y_E = Thermal Diffusivity, m^2/sec

X = Temperature, °K

b, a	COEFFICIENT	STANDARD ERROR
b_0	7.7971×10^{-6}	--------------
a_1	4.6076×10^{-9}	1.9052×10^{-9}
a_2	-4.4006×10^{-12}	1.2085×10^{-12}

Multiple Correlation = .9043

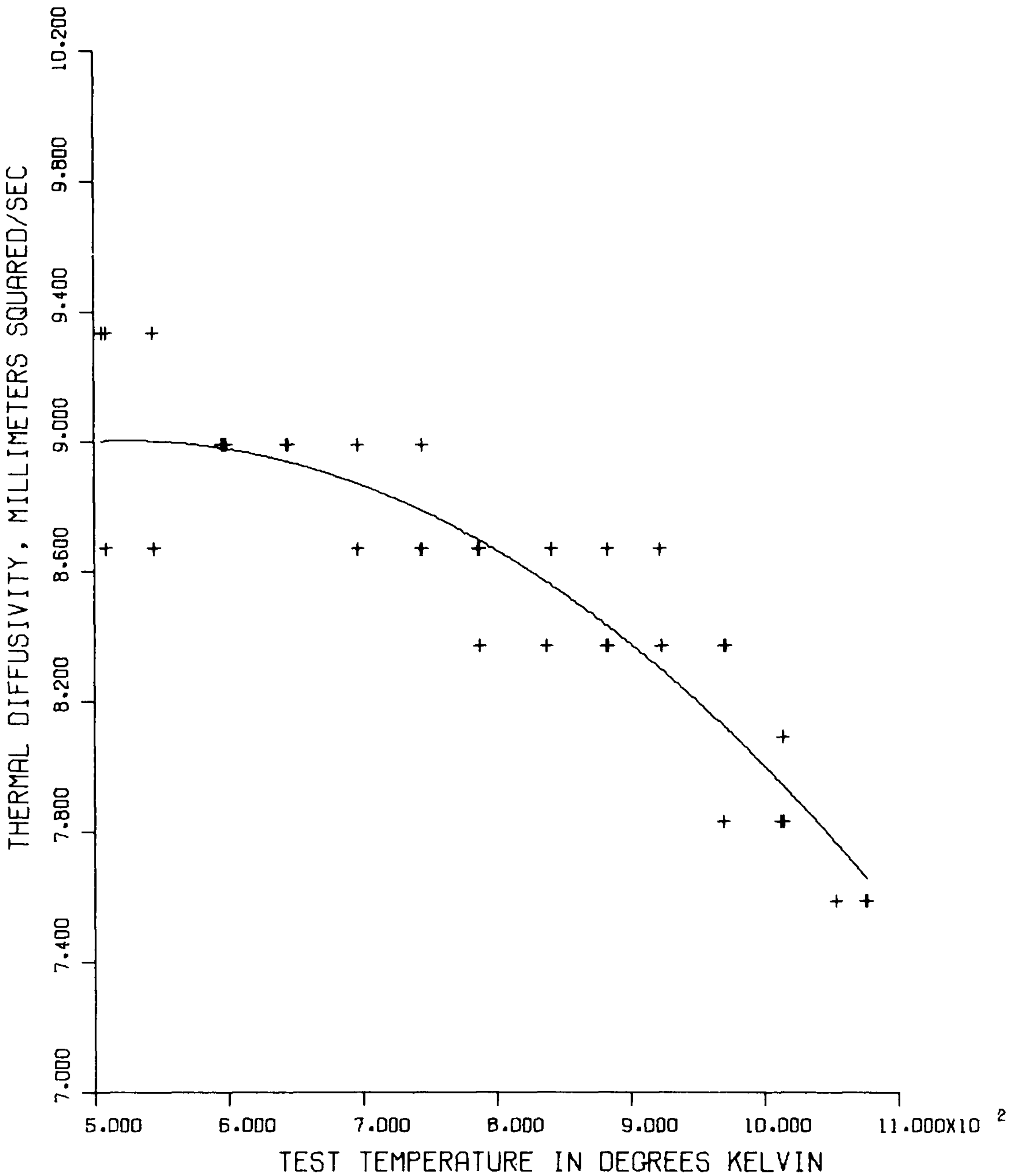
Std. Error of Estimate = 2.0589×10^{-7}

F statistic of regression = 81.00

F critical = 3.23

$\nu_1 = 2,\ \nu_2 = 36,\ \alpha = 0.05$

FIGURE 5



ALLOY E - T. D. VS. TEMPERATURE

TABLE XIV

THERMAL DIFFUSIVITY CURVE FITTING

WITH POLYNOMIAL REGRESSION - ALLOY F

$$Y_F = b_0 + a_1(X^1) + a_2(X^2)$$

Y_F = Thermal Diffusivity, m^2/sec

X = Temperature, °K

b, a	COEFFICIENT	STANDARD ERROR
b_0	1.0805×10^{-5}	--------------
a_1	-5.7476×10^{-9}	2.1654×10^{-9}
a_2	2.3975×10^{-12}	1.3534×10^{-12}

Multiple Correlation = .8304

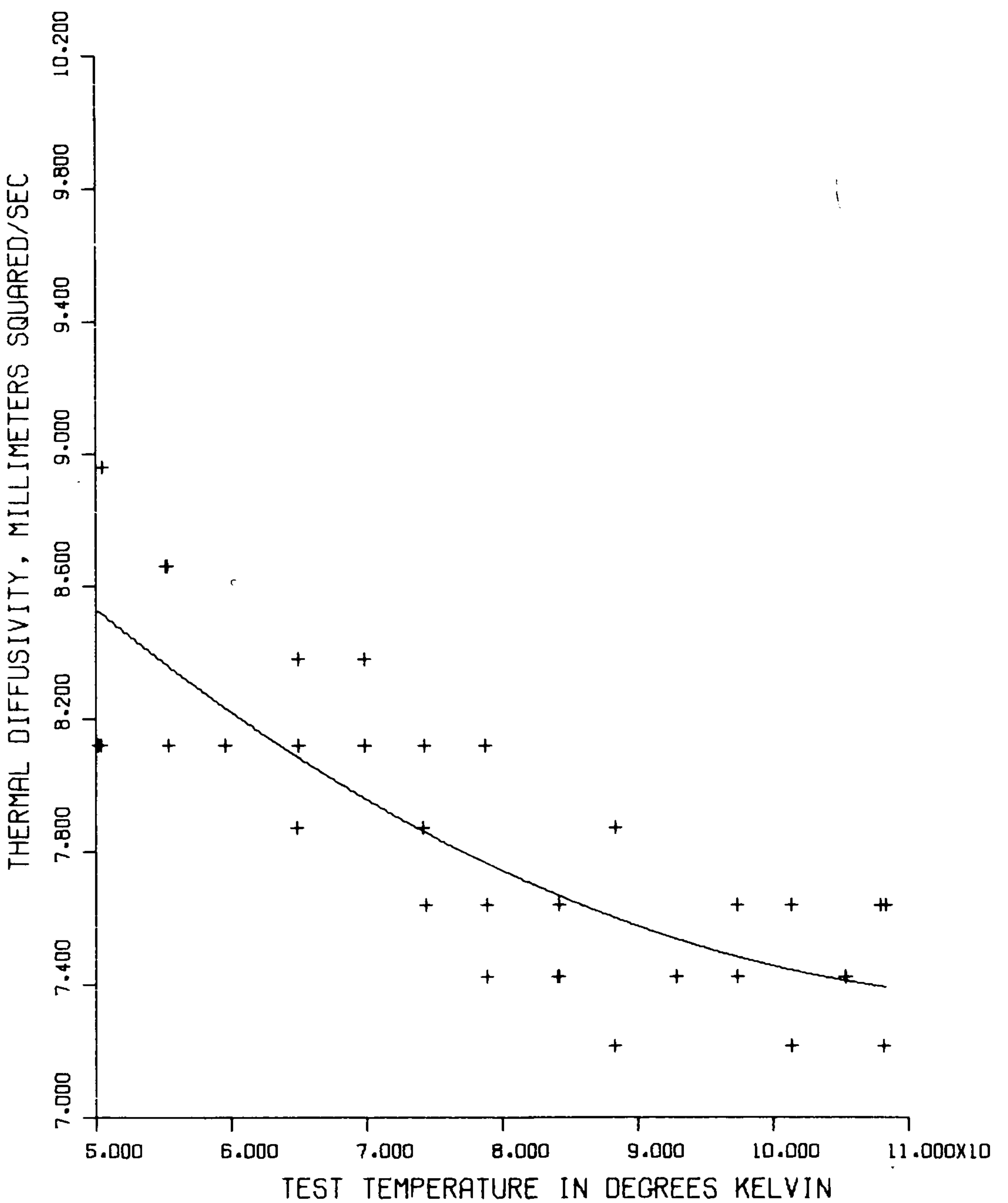
Std. Error of Estimate = 2.4967×10^{-7}

F statistic of regression = 41.09

F - critical = 3.23

$\nu_1 = 2,\ \nu_2 = 37,\ \alpha = 0.05$

FIGURE 6



ALLOY F - T. D. VS. TEMPERATURE

TABLE XV

THERMAL DIFFUSIVITY CURVE FITTING

WITH POLYNOMIAL REGRESSION - ALLOY G

$$Y_G = b_0 + a_1(X^1) + a_2(X^2)$$

Y_G = Thermal Diffusivity, m^2/sec

X = Temperature, °K

b, a	COEFFICIENT	STANDARD ERROR
b_0	1.2960×10^{-5}	--------------
a_1	-8.2649×10^{-9}	1.6460×10^{-9}
a_2	3.4221×10^{-12}	1.0282×10^{-12}

Multiple Correlation = .9444

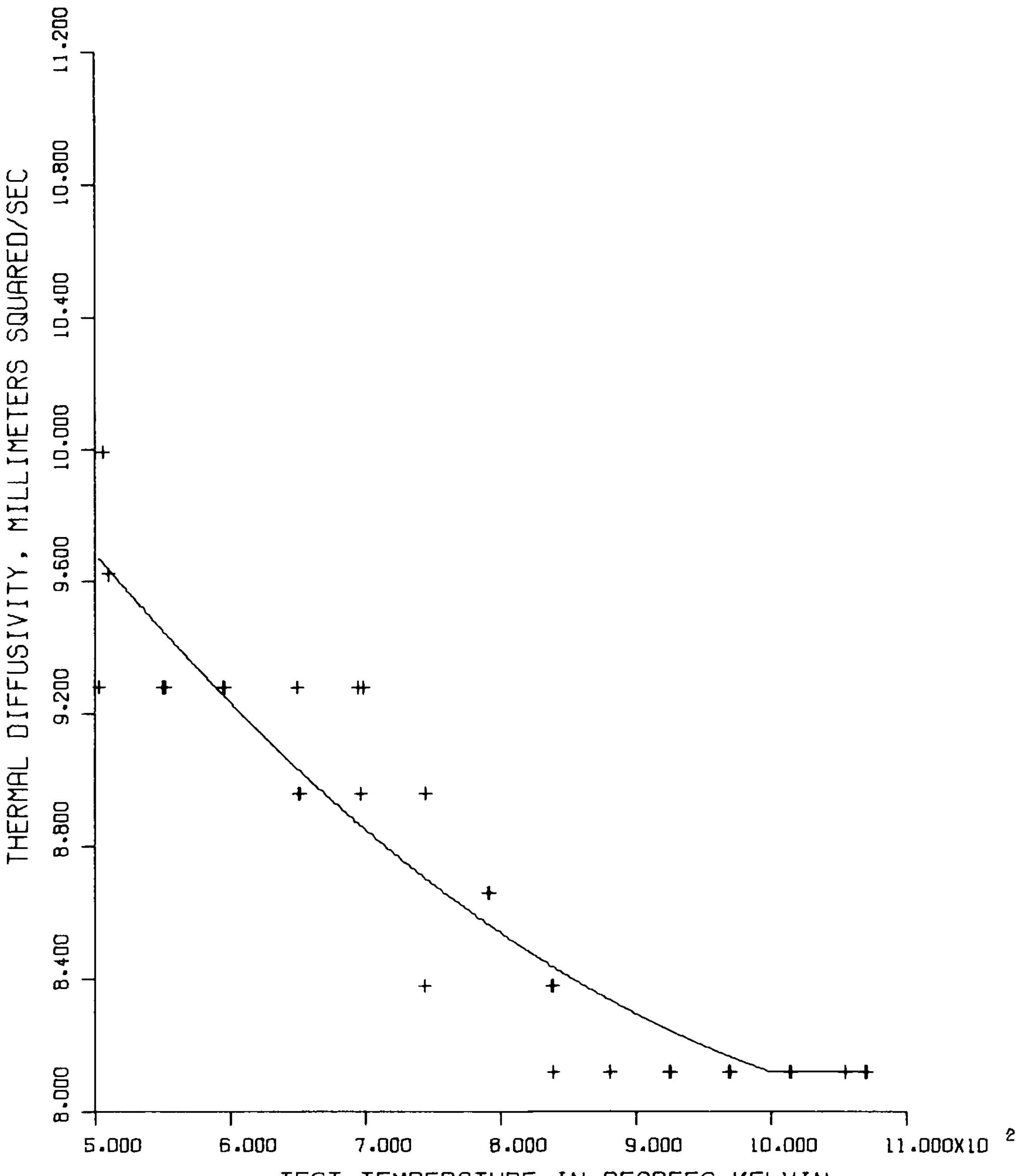
Std. Error of Estimate = 1.8802×10^{-12}

F statistic of regression = 160.72

F - critical = 3.23

$\nu_1 = 2$, $\nu_2 = 39$, $\alpha = 0.05$

FIGURE 7



ALLOY G - T. D. VS. TEMPERATURE

TABLE XVI

CALCULATED THERMAL DIFFUSIVITIES

OF EXPERIMENTAL ALLOYS

ALLOY CODE	THERMAL DIFFUSIVITY, x 10^{-6} m^2/sec			
	473.15°K (200°C)	673.15°K (400°C)	873.15°K (600°C)	1073.15°K (800°C)
A	9.852	8.927	8.133	7.468
B	8.973	8.308	7.696	7.138
C	9.041	8.591	8.060	7.449
D	9.517	8.789	8.261	7.934
E	8.992	8.905	8.465	7.674
F	8.622	8.022	7.614	7.398
G	9.816	8.947	8.352	8.032

Performance Characterization

The performance of the seven experimental steel cutting grades of tungsten carbide was determined for the three cutting conditions. The reader may wish to review the three conditions at this point; they are found in Table IV.

The raw data, shown in Appendix B, reveal the parameters which were monitored and recorded for each cut. As Appendix B indicates, wear was measured only after nine minutes of cutting for all alloys. After reviewing Scheithauer's work, it was felt that the measuring of wear after 1,3,5,7, and 9 minutes was not necessary, as he proved that 9 minutes of cutting would still be yielding wear values which were on the straight, gradual wear part of the total wear curve.

From the data in Appendix B, averages for the six independent readings taken for each wear sample were computed. All of these averages for flank and nose wear for replicates one and two, at each condition, are found in Tables XVII,XVIII,XIX,XX,XXI, and XXII. From these tables, the average for both replicates was calculated for each wear sample. These averages are found in Tables XXIII, XXIV, and XXV, and are shown rounded to the maximum number of significant digits possible in reading the toolmaker's microscope. The microscope is graduated in mils, and can be read to the nearest .0001". Thus, all wear values are shown as converted to metric units: micrometers (μm).

TABLE XVII

FLANK AND NOSE WEAR FOR CONDITION ONE - REPLICATE ONE

ALLOY CODE	FLANK WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	24.9(1.0)	3.0(0.1)
B	30.5(1.2)	2.8(0.1)
C	42.4(1.7)	3.8(0.2)
D	62.2(2.5)	3.6(0.1)
E	29.2(1.2)	3.8(0.2)
F	35.1(1.4)	3.3(0.1)
G	36.8(1.5)	4.1(0.2)

ALLOY CODE	NOSE WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	53.8(2.1)	3.0(0.1)
B	83.1(3.3)	3.0(0.1)
C	59.7(2.4)	7.4(0.3)
D	81.8(3.2)	3.8(0.2)
E	48.3(1.9)	3.3(0.1)
F	74.9(3.0)	5.3(0.2)
G	54.1(2.1)	5.1(0.2)

TABLE XVIII

FLANK AND NOSE WEAR FOR CONDITION TWO - REPLICATE ONE

ALLOY CODE	FLANK WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	53.8(2.1)	4.8(0.2)
B	81.8(3.2)	3.8(0.2)
C	96.0(3.8)	4.6(0.2)
D	63.0(2.5)	4.3(0.2)
E	45.2(1.8)	2.5(0.1)
F	73.7(2.9)	4.6(0.2)
G	60.5(2.4)	2.5(0.1)

ALLOY CODE	NOSE WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	90.9(3.4)	2.0(0.1)
B	121.2(4.8)	3.8(0.2)
C	141.0(5.6)	7.1(0.3)
D	93.5(3.7)	4.6(0.2)
E	62.7(2.5)	3.0(0.1)
F	88.9(3.5)	6.4(0.3)
G	79.5(3.1)	2.0(0.1)

TABLE XIX

FLANK AND NOSE WEAR FOR CONDITION THREE - REPLICATE ONE

ALLOY CODE	FLANK WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	173.5(6.8)	6.1(0.2)
B	248.4(9.8)	12.2(0.5)
C	285.0(11.2)	15.0(0.6)
D	281.9(11.1)	6.6(0.3)
E	250.2(9.9)	17.0(0.7)
F	303.5(12.0)	12.4(0.5)
G	230.4(9.1)	17.0(0.7)

ALLOY CODE	NOSE WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	632.0(24.9)	18.5(0.7)
B	759.5(29.9)	20.3(0.8)
C	725.2(28.6)	16.5(0.7)
D	1170.4(46.1)	37.6(1.5)
E	618.5(24.4)	27.7(1.1)
F	950.0(12.0)	33.3(1.3)
G	665.5(26.2)	91.7(3.6)

TABLE XX

FLANK AND NOSE WEAR FOR CONDITION ONE - REPLICATE TWO

ALLOY CODE	FLANK WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	27.4(1.1)	3.8(0.2)
B	28.7(1.1)	2.0(0.1)
C	45.7(1.8)	3.3(0.1)
D	51.3(2.0)	5.3(0.2)
E	25.9(1.0)	4.1(0.2)
F	28.3(1.1)	3.0(0.1)
G	33.8(1.3)	2.0(0.1)

ALLOY CODE	NOSE WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	66.6(2.6)	8.1(0.3)
B	92.0(3.6)	6.9(0.3)
C	70.6(2.8)	8.9(0.4)
D	72.9(2.9)	8.4(0.3)
E	45.0(1.8)	5.8(0.2)
F	62.7(2.5)	7.9(0.3)
G	59.2(2.3)	2.0(0.1)

TABLE XXI

FLANK AND NOSE WEAR FOR CONDITION TWO - REPLICATE TWO

ALLOY CODE	FLANK WEAR, μm(mils) - $\overline{X}$, σ OF SIX READINGS	
	MEAN, $\overline{X}$	STD. DEVIATION, σ
A	59.2(2.3)	3.8(0.2)
B	83.1(3.3)	5.1(0.2)
C	97.3(3.8)	4.0(0.2)
D	70.4(2.8)	3.8(0.2)
E	62.7(2.5)	2.5(0.1)
F	64.0(2.5)	7.1(0.3)
G	50.8(2.0)	3.3(0.1)

ALLOY CODE	NOSE WEAR, μm(mils) - $\overline{X}$, σ OF SIX READINGS	
	MEAN, $\overline{X}$	STD. DEVIATION, σ
A	110.0(4.3)	6.6(0.3)
B	155.7(6.1)	6.4(0.3)
C	108.7(4.3)	8.1(0.3)
D	80.8(3.2)	4.3(0.2)
E	84.3(3.3)	4.3(0.2)
F	80.5(3.2)	7.4(0.3)
G	71.1(2.8)	2.8(0.1)

TABLE XXII

FLANK AND NOSE WEAR FOR CONDITION THREE - REPLICATE TWO

ALLOY CODE	FLANK WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	176.6(7.0)	6.9(0.3)
B	211.6(8.3)	10.2(0.4)
C	315.7(12.4)	11.2(0.4)
D	244.7(9.6)	5.8(0.2)
E	258.3(10.2)	10.4(0.4)
F	291.3(11.5)	40.4(1.6)
G	203.2(8.0)	4.8(0.2)

ALLOY CODE	NOSE WEAR, μm(mils) - $\bar{X}$, σ OF SIX READINGS	
	MEAN, $\bar{X}$	STD. DEVIATION, σ
A	647.1(25.5)	16.3(0.6)
B	655.5(25.8)	20.1(0.8)
C	779.3(30.7)	11.7(0.5)
D	924.7(36.4)	26.4(1.0)
E	838.7(33.0)	14.2(0.6)
F	1109.4(43.7)	33.5(1.3)
G	695.5(27.4)	21.6(0.9)

TABLE XXIII

FLANK AND NOSE WEAR FOR CONDITION ONE - AVERAGE

ALLOY CODE	FLANK WEAR, μm(mils) - $\bar{X}$ OF TWO REPLICATES
A	26.(1.0)
B	30.(1.2)
C	44.(1.7)
D	57.(2.2)
E	28.(1.1)
F	32.(1.3)
G	35.(1.4)

ALLOY CODE	NOSE WEAR, μm(mils) - $\bar{X}$ OF TWO REPLICATES
A	60.(2.4)
B	88.(3.5)
C	65.(2.6)
D	77.(3.0)
E	47.(1.9)
F	69.(2.7)
G	57.(2.2)

TABLE XXIV

FLANK AND NOSE WEAR FOR CONDITION TWO - AVERAGE

ALLOY CODE	FLANK WEAR, μm(mils) - $\overline{X}$ OF TWO REPLICATES
A	57.(2.2)
B	82.(3.2)
C	97.(3.8)
D	67.(2.6)
E	54.(2.1)
F	69.(2.7)
G	56.(2.2)

ALLOY CODE	NOSE WEAR, μm(mils) - $\overline{X}$ OF TWO REPLICATES
A	100.(3.9)
B	138.(5.4)
C	125.(4.9)
D	88.(3.5)
E	74.(2.9)
F	85.(3.3)
G	76.(3.0)

TABLE XXV

FLANK AND NOSE WEAR FOR CONDITION THREE - AVERAGE

ALLOY CODE	FLANK WEAR, µm(mils) - $\bar{X}$ OF TWO REPLICATES
A	176.(6.9)
B	230.(9.1)
C	301.(11.9)
D	264.(10.4)
E	254.(10.0)
F	298.(11.7)
G	217.(8.5)

ALLOY CODE	NOSE WEAR, µm(mils) - $\bar{X}$ OF TWO REPLICATES
A	640.(25.2)
B	708.(27.9)
C	752.(29.6)
D	1048.(41.3)
E	729.(28.7)
F	1030.(40.6)
G	681.(26.8)

Correlation of Properties and Performance

The dependent variables (Y_i) used throughout the correlation analyses were the flank and nose wear values measured after nine minutes of cutting. Three different groups of dependent variables, along with their coding and identification, are listed in Tables XXVI,XXVII, and XXVIII. Replicate one results are shown in Table XXVI, replicate two in Table XXVII, and the averages of replicate one and two are listed in Table XXVIII. A fourth group of dependent variables, made from the combination of replicates one and two (Tables XXVI and XXVII), will also be subjected to stepwise regression analysis, along with the first three.

The independent variables (X_i) that were previously shown in Tables V,VI,VII,VIII, and XVI are summarized, coded, and identified in Table XXIX, printed on pages 66-67.

The coding for all dependent and independent variables in Tables XXVI-XXIX will be used throughout the remainder of the analyses, and therefore, these tables should be referred to when the reader views all regression results and summaries.

The subjecting of the four groups of dependent variables, i.e. replicate one, replicate two, average of both

TABLE XXVI

DEPENDENT VARIABLES IDENTIFICATION - REPLICATE ONE

	DEPENDENT VARIABLES - FLANK OR NOSE WEAR(1)					
ALLOY CODE	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
A	25.	54.	54.	91.	174.	632.
B	31.	83.	82.	121.	248.	760.
C	42.	60.	96.	141.	285.	725.
D	62.	82.	63.	94.	282.	1170.
E	29.	48.	45.	63.	250.	619.
F	35.	75.	74.	89.	304.	950.
G	37.	54.	61.	80.	230.	666.

Y_1 = Flank Wear for Condition One

Y_2 = Nose Wear for Condition One

Y_3 = Flank Wear for Condition Two

Y_4 = Nose Wear for Condition Two

Y_5 = Flank Wear for Condition Three

Y_6 = Nose Wear for Condition Three

(1) Flank and nose wear in μm taken from Tables

TABLE XXVII

DEPENDENT VARIABLES IDENTIFICATION - REPLICATE TWO

ALLOY CODE	DEPENDENT VARIABLES - FLANK OR NOSE WEAR[1]					
	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
A	27.	67.	59.	110.	177.	647.
B	29.	92.	83.	156.	212.	655.
C	46.	71.	97.	109.	316.	779.
D	51.	73.	70.	81.	245.	925.
E	26.	45.	63.	84.	258.	839.
F	29.	63.	64.	81.	291.	1109.
G	34.	59.	51.	71.	203.	696.

Y_1 = Flank Wear for Condition One

Y_2 = Nose Wear for Condition One

Y_3 = Flank Wear for Condition Two

Y_4 = Nose Wear for Condition Two

Y_5 = Flank Wear for Condition Three

Y_6 = Nose Wear for Condition Three

(1) Flank and nose wear in μm taken from Tables

TABLE XXVIII

DEPENDENT VARIABLES IDENTIFICATION - AVERAGE OF REPLICATES

	DEPENDENT VARIABLES - FLANK OR NOSE WEAR[1]					
ALLOY CODE	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
A	26.	60.	57.	100.	176.	640.
B	30.	88.	82.	138.	230.	708.
C	44.	65.	97.	125.	301.	752.
D	57.	77.	67.	88.	264.	1048.
E	28.	47.	54.	74.	254.	729.
F	32.	69.	69.	85.	298.	1030.
G	35.	57.	56.	76.	217.	681.

Y_1 = Flank Wear for Condition One

Y_2 = Nose Wear for Condition One

Y_3 = Flank Wear for Condition Two

Y_4 = Nose Wear for Condition Two

Y_5 = Flank Wear for Condition Three

Y_6 = Nose Wear for Condition Three

(1) Flank and nose wear in μm taken from Tables

TABLE XXIX

INDEPENDENT VARIABLES IDENTIFICATION

ALLOY CODE	INDEPENDENT VARIABLES - MEASURED PROPERTIES									
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}
A	1.43	12.55	154.	1520.	92.0	1560.	1017.	790.	1.471	21.5
B	1.74	12.49	121.	1503.	91.3	1500.	967.	775.	1.391	22.5
C	1.60	12.47	119.	1442.	91.2	1469.	908.	760.	1.848	26.2
D	1.98	12.50	115.	1464.	91.2	1439.	997.	766.	1.447	24.5
E	1.70	12.61	118.	1443.	91.4	1463.	975.	763.	1.242	26.5
F	1.63	12.56	119.	1439.	91.5	1494.	917.	733.	1.377	22.1
G	1.82	12.59	113.	1410.	91.3	1494.	1003.	734.	1.575	25.0

x_1 = grain size, x_2 = density, x_3 = coercive force, x_4 = DPH at 298.15°K, x_5 = R_a at 298.15°K, x_6 = Vickers hardness at 298.15°K, x_7 = Vickers hardness at 673.15°K, x_8 = Vickers hardness at 1073.15°K, x_9 = TRS at 298.15°K, x_{10} = abrasion factor.

TABLE XXIX (continued)

INDEPENDENT VARIABLES IDENTIFICATION

ALLOY CODE	INDEPENDENT VARIABLES - MEASURED PROPERTIES						
	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}
A	45.01	17.42	13.33	9.852	8.927	8.133	7.468
B	43.40	15.52	12.32	8.973	8.308	7.696	7.138
C	43.68	18.62	12.91	9.041	8.591	8.060	7.449
D	38.77	15.50	12.80	9.517	8.789	8.261	7.934
E	38.69	15.75	12.00	8.992	8.905	8.465	7.674
F	32.66	15.16	12.70	8.622	8.022	7.614	7.398
G	33.96	15.81	11.00	9.816	8.947	8.352	8.032

x_{11} = fracture toughness at 298.15°K, x_{12} = fracture toughness at 673.15°K, x_{13} = fracture toughness at 1073.15°K, x_{14} = thermal diffusivity at 473.15°K, x_{15} = thermal diffusivity at 673.15°K, x_{16} = thermal diffusivity at 873.15°K, x_{17} = thermal diffusivity at 1073.15°K.

replicates, and replicate one and two combined, to stepwise regressions partially because of experimental design, but mostly because of the author's curiousity as to what the results would be from regressions run on data which is essentially statistically the same. The data is "statistically the same" by virtue of the fact that it was produced from the same cutting situations.

One could never expect to see exactly equal results from any number of replications, in fact, this is exactly why replications are made: to provide a check for obvious errors, and to produce smaller and smaller standard deviations for the variables measured, by increasing the number of observations made for each variable studied.

Therefore, even though replicate one and two are slightly quantitatively different due to experimental variation, we would expect fairly similar results from stepwise regressions run on the individual replications. The average of the replications should also produce similar results, After all, the average of any number of replications is often used as a final value in further analyses, as did Scheithauer in his attempt to correlate properties and performance.[1] Simultaneous feeding of the raw data from replicate one and replicate two into stepwise regressions should, again, produce results similar to the first three cases, and especially similar results should be found for the regressions run with the average data, and with the combination of replicate one and two.

By similar, it is meant that the stepwise regressions should produce results which indicate that no matter which group of data is used, the order of the first three or four variables chosen by the regression to reduce the variance per step should remain essentially the same. The sign, positive or negative, of the independent variable's coefficient should also remain the same. Of course we would not expect the value of the coefficients to be the same.

The data found in Tables XXVI, XXVII, XXVIII, and XXIX were analyzed using the LEAPS statistical package[21] and the BMD statistical package.[22] The results for replicate one, replicate two, the average of replicates one and two, and for replicate one combined with replicate two are shown in Tables XXX,XXXI,XXXII, and XXXIII respectively. The first four, out of the total seventeen variables allowed to enter, variables dropped out by the regression in order of importance in explaining the variance are listed. In almost all cases, approximately 95%, or more, of the total variance was explained by the first four variables.

Other regression statistics are not shown for two

TABLE XXX

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR
(ALL INDEPENDENT VARIABLES - REPLICATE ONE)

	Condition One		Condition Two		Condition Three	
Independent Property	Flank	Nose	Flank	Nose	Flank	Nose
x_1 - Grain Size	↑(1)	↑(2)	NE	NE	NE	↑(1)
x_2 - Density	↑(4)	NE	↓(1)	↓(1)	NE	NE
x_3 - Coercive Force	NE	NE	NE	NE	↓(1)	NE
x_4 - DPH at 298.15°K	NE	↑(4)	NE	NE	NE	NE
x_5 - R_a at 298.15°K	NE	NE	↑(4)	NE	NE	NE
x_6 - Vickers Hardness at 298.15°K	NE	NE	NE	NE	NE	NE
x_7 - Vickers Hardness at 673.15°K	NE	NE	↓(2)	NE	NE	NE
x_8 - Vickers Hardness at 1073.15°K	NE	NE	NE	NE	↓(3)	NE
x_9 - TRS at 298.15°K	↑(3)	NE	NE	↑(2)	NE	NE
x_{10} - Abrasion Factor	NE	NE	NE	NE	NE	NE
x_{11} - Fracture Toughness at 298.15°K	NE	NE	NE	NE	NE	↓(3)
x_{12} - Fracture Toughness at 673.15°K	NE	NE	NE	NE	NE	NE
x_{13} - Fracture Toughness at 1073.15°K	↑(2)	↑(3)	↓(3)	↓(4)	↑(2)	↑(2)
x_{14} - Thermal Diffusivity at 473.15°K	NE	NE	NE	NE	↓(4)	NE
x_{15} - Thermal Diffusivity at 673.15°K	NE	NE	NE	NE	NE	NE
x_{16} - Thermal Diffusivity at 873.15°K	NE	↓(1)	NE	NE	NE	↓(4)
x_{17} - Thermal Diffusivity at 1073.15°K	NE	NE	NE	↓(3)	NE	NE

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

TABLE XXXI

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR
(ALL INDEPENDENT VARIABLES - REPLICATE TWO)

Independent Property	Condition One		Condition Two		Condition Three	
	Flank	Nose	Flank	Nose	Flank	Nose
x_1 - Grain Size	NE	NE	NE	↑(3)	NE	NE
x_2 - Density	NE	↓(1)	↓(1)	NE	NE	NE
x_3 - Coercive Force	NE	NE	↓(4)	NE	NE	NE
x_4 - DPH at 298.15°K	NE	↑(4)	NE	NE	NE	NE
x_5 - Ra at 298.15°K	NE	NE	NE	NE	↑(3)	NE
x_6 - Vickers Hardness at 298.15°K	↓(1)	NE	NE	↑(4)	↓(2)	↓(3)
x_7 - Vickers Hardness at 673.15°K	NE	NE	↓(2)	NE	↓(1)	NE
x_8 - Vickers Hardness at 1073.15°K	NE	NE	NE	NE	NE	NE
x_9 - TRS at 298.15°K	↑(2)	NE	NE	NE	NE	NE
x_{10} - Abrasion Factor	↓(3)	↓(2)	NE	NE	NE	NE
x_{11} - Fracture Toughness at 298.15°K	NE	NE	↑(3)	↑(2)	NE	↓(1)
x_{12} - Fracture Toughness at 673.15°K	NE	NE	NE	NE	NE	NE
x_{13} - Fracture Toughness at 1073.15°K	NE	↓(3)	NE	NE	NE	↑(2)
x_{14} - Thermal Diffusivity at 473.15°K	NE	NE	NE	NE	↑(4)	↓(4)
x_{15} - Thermal Diffusivity at 673.15°K	↑(4)	NE	NE	NE	NE	NE
x_{16} - Thermal Diffusivity at 873.15°K	NE	NE	NE	NE	NE	NE
x_{17} - Thermal Diffusivity at 1073.15°K	NE	NE	NE	↓(1)	NE	NE

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

TABLE XXXII

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR
(ALL INDEPENDENT VARIABLES - AVERAGE OF REPLICATES)

Independent Property	Condition One		Condition Two		Condition Three	
	Flank	Nose	Flank	Nose	Flank	Nose
x_1 - Grain Size	NE	NE	NE	NE	↓(4)	NE
x_2 - Density	↓(2)	↓(1)	↓(1)	↓(1)	NE	NE
x_3 - Coercive Force	NE	NE	NE	NE	NE	NE
x_4 - DPH at 298.15°K	NE	NE	NE	NE	NE	↓(4)
x_5 - R_a at 298.15°K	NE	↓(4)	NE	NE	↓(3)	↑(3)
x_6 - Vickers Hardness at 298.15°K	↓(1)	↑(3)	NE	NE	↑(2)	↓(1)
x_7 - Vickers Hardness at 673.15°K	NE	NE	↓(2)	NE	↑(1)	NE
x_8 - Vickers Hardness at 1073.15°K	NE	NE	NE	NE	NE	NE
x_9 - TRS at 298.15°K	NE	NE	NE	NE	NE	NE
x_{10} - Abrasion Factor	NE	NE	NE	NE	NE	↓(2)
x_{11} - Fracture Toughness at 298.15°K	NE	NE	↑(4)	NE	NE	NE
x_{12} - Fracture Toughness at 673.15°K	NE	↓(2)	NE	NE	NE	NE
x_{13} - Fracture Toughness at 1073.15°K	↑(4)	NE	↓(3)	↓(3)	NE	NE
x_{14} - Thermal Diffusivity at 473.15°K	NE	NE	NE	NE	NE	NE
x_{15} - Thermal Diffusivity at 673.15°K	NE	NE	NE	↑(4)	NE	NE
x_{16} - Thermal Diffusivity at 873.15°K	NE	NE	NE	NE	NE	NE
x_{17} - Thermal Diffusivity at 1073.15°K	↑(3)	NE	NE	↓(2)	NE	NE

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

TABLE XXXIII

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR
(ALL INDEPENDENT VARIABLES - REPLICATES ONE AND TWO)

Independent Property	Condition One		Condition Two		Condition Three	
	Flank	Nose	Flank	Nose	Flank	Nose
x_1 - Grain Size	NE	NE	NE	NE	↑(4)	NE
x_2 - Density	↓(2)	↓(1)	↓(1)	↓(1)	NE	NE
x_3 - Coercive Force	NE	NE	NE	NE	NE	NE
x_4 - DPH at 298.15°K	NE	NE	NE	NE	NE	↓(4)
x_5 - R_a at 298.15°K	NE	↓(4)	NE	NE	↑(3)	↑(3)
x_6 - Vickers Hardness at 298.15°K	↓(1)	↑(3)	NE	NE	↓(2)	↓(1)
x_7 - Vickers Hardness at 673.15°K	NE	NE	↓(2)	NE	↓(1)	NE
x_8 - Vickers Hardness at 1073.15°K	NE	NE	NE	NE	NE	NE
x_9 - TRS at 298.15°K	NE	NE	NE	NE	NE	NE
x_{10} - Abrasion Factor	↑(4)	NE	NE	NE	NE	↓(2)
x_{11} - Fracture Toughness at 298.15°K	NE	NE	↑(4)	NE	NE	NE
x_{12} - Fracture Toughness at 673.15°K	NE	↓(2)	NE	NE	NE	NE
x_{13} - Fracture Toughness at 1073.15°K	NE	NE	↓(3)	↓(3)	NE	NE
x_{14} - Thermal Diffusivity at 473.15°K	NE	NE	NE	NE	NE	NE
x_{15} - Thermal Diffusivity at 673.15°K	NE	NE	NE	↑(4)	NE	NE
x_{16} - Thermal Diffusivity at 873.15°K	NE	NE	NE	NE	NE	NE
x_{17} - Thermal Diffusivity at 1073.15°K	↑(3)	NE	NE	↓(2)	NE	NE

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

reasons. The first reason was because the statistics are not of primary importance at this point, and the second reason was because the method which was used in generating stepwise regressions, so far, produces erroneous regression statistics.

Tables XXX,XXXI,XXXII, and XXXIII show the first four independent variables entered, their order of importance in explaining variance, and the sign of the variable's coefficient; the arrow indicates the direction that the independent variable must move to cause increasing wear. For the sake of easy comparison of results, Tables XXX, XXXI,XXXII, and XXXIII are summarized in Table XXXIV.

As far as which variables entered as being most important in defining performance, the results shown indicate the same as did Scheithauers'.[1] Except for density, which seemed to enter on many occasions, seldom do we see the commonly measured properties ever enter as being important. Also, many of those properties entered were elevated temperature properties.

What seems to be more important, at this point, than which properties enter, is the fact that using the different groups of data produced results such as shown in Table XXXIV. This summary is, at least, disturbing. The same variables, in the same order and with the same sign, do not always enter for any one condition. Even the re-

TABLE XXXIV

COMPARISON OF RESULTS FOR DIFFERENT DATA GROUPS[1]

(ALL INDEPENDENT VARIABLES)

CONDITION ONE

	Replicate One		Replicate Two		Average of Replicates		Replicate One and Two	
Role	Flank	Nose	Flank	Nose	Flank	Nose	Flank	Nose
Primary	$\uparrow x_1$	$\downarrow x_{16}$	$\downarrow x_6$	$\downarrow x_2$	$\downarrow x_6$	$\downarrow x_2$	$\downarrow x_6$	$\downarrow x_2$
Secondary	$\uparrow x_{13}$	$\uparrow x_1$	$\uparrow x_9$	$\downarrow x_{10}$	$\downarrow x_2$	$\downarrow x_{12}$	$\downarrow x_2$	$\downarrow x_{12}$
Tertiary	$\uparrow x_9$	$\uparrow x_{13}$	$\downarrow x_{10}$	$\downarrow x_{13}$	$\uparrow x_{17}$	$\uparrow x_6$	$\uparrow x_{17}$	$\uparrow x_6$
Quaternary	$\uparrow x_2$	$\uparrow x_4$	$\uparrow x_{15}$	$\uparrow x_4$	$\uparrow x_{13}$	$\downarrow x_5$	$\uparrow x_{10}$	$\downarrow x_5$

CONDITION TWO

	Replicate One		Replicate Two		Average of Replicates		Replicate One and Two	
Role	Flank	Nose	Flank	Nose	Flank	Nose	Flank	Nose
Primary	$\downarrow x_2$	$\downarrow x_2$	$\downarrow x_2$	$\downarrow x_{17}$	$\downarrow x_2$	$\downarrow x_2$	$\downarrow x_2$	$\downarrow x_2$
Secondary	$\downarrow x_7$	$\uparrow x_9$	$\downarrow x_7$	$\uparrow x_{11}$	$\downarrow x_7$	$\downarrow x_{17}$	$\downarrow x_7$	$\downarrow x_{17}$
Tertiary	$\downarrow x_{13}$	$\downarrow x_{17}$	$\uparrow x_{11}$	$\uparrow x_1$	$\downarrow x_{13}$	$\downarrow x_{13}$	$\downarrow x_{13}$	$\downarrow x_{13}$
Quaternary	$\uparrow x_5$	$\downarrow x_{13}$	$\downarrow x_{13}$	$\uparrow x_6$	$\uparrow x_{11}$	$\uparrow x_{15}$	$\uparrow x_{11}$	$\uparrow x_{15}$

CONDITION THREE

	Replicate One		Replicate Two		Average of Replicates		Replicate One and Two	
Role	Flank	Nose	Flank	Nose	Flank	Nose	Flank	Nose
Primary	$\downarrow x_3$	$\uparrow x_1$	$\downarrow x_7$	$\downarrow x_{11}$	$\downarrow x_7$	$\downarrow x_6$	$\downarrow x_7$	$\downarrow x_6$
Secondary	$\uparrow x_{13}$	$\uparrow x_{13}$	$\downarrow x_6$	$\uparrow x_{13}$	$\downarrow x_6$	$\downarrow x_{10}$	$\downarrow x_6$	$\downarrow x_{10}$
Tertiary	$\downarrow x_8$	$\downarrow x_{11}$	$\uparrow x_5$	$\downarrow x_6$	$\uparrow x_5$	$\uparrow x_5$	$\uparrow x_5$	$\uparrow x_5$
Quaternary	$\downarrow x_{14}$	$\downarrow x_{16}$	$\uparrow x_{14}$	$\downarrow x_{14}$	$\uparrow x_1$	$\downarrow x_4$	$\uparrow x_1$	$\downarrow x_4$

[1] The arrows show the direction of the property to cause increasing wear.

sults shown for the average of the two replicates, and the combination of replicate one and two, indicate some disagreement. Note that even the variables which enter first (primary) do not always agree for all four data groups. Sometimes the same variables enter for all groups, but then the signs are in disagreement. It is also shown that if the average value was used as being the true value, the results are sometimes different from either replicate's data used alone; note condition three, nose wear.

All of the stepwise regressions showed exceptionally high amounts of variance explained by regression (R^2); correlations at the 99% level were not uncommon. It seems that, to some degree, the choice of the four most important variables is arbitrary, as different combinations of four variables will produce almost equally good results.

It is then concluded that a fine line of difference is sometimes seen between any two candidates available for the regression to enter at some step. Minor variations in wear sample measurements, made for the same condition, obviously can have a significant effect on stepwise regression results. Therefore, it is difficult to place a high level of certainty on any of the results for some data group shown in Table XXXIV.

Before proceeding with the discussion, it should be noted that certain areas of precaution with regard to the use of regression equations should be taken into account.

1. Regression equations can be very misleading when used as predictors outside the range of the independent variables used to generate the equation.

2. It is semi-dangerous to use them at all unless some physical significance can be offered to explain the relationship between each independent variable and the dependent variable.

3. The regression equation describes the particular set of data, and is not necessarily a law which describes the source from which the data is drawn.

Number three (3.) above is particularly applicable here, as we have seen that different data groups from the same conditions can result in different regression equations. Any particular regression resulted equation is then only accurate for the specific set of data used in computing the equation, and in no way could it be used for predicting performance for any other cutting condition, no matter how small the change. Nor could it be used to predict outside of the range of independent variables used in generating the equation. A grim picture is seemingly being painted here, as it seems that not only can an equation never be used to predict performance outside the range of its independent variables, nor for different conditions, but, neither can it be deemed reliable within the range of the independent variables. Table XXXIV proves this, as it shows that different replications of any one condition would result in a different, regression calculated, predicting equation.

There are other problems involved with the regression analyses described herein. When running regressions, most statistical packages require that the number of observations be at least one more than the number of variables. In fact, it is recommended that the number of observations be equal to two, or preferably three to four times the number of variables. The number of observations for this analysis of correlation of properties and performance was equal to the number of tool alloys, i.e. seven. Thus, to obtained the results shown in Tables XXX through XXXIV, the seven observations had to be duplicated three times. This number arises from the existence of seventeen independent variables, which were always regressed against one dependent variable; flank or nose wear. The total number of variables in each regression was, therefore, eighteen, and three copies of the original seven observations was the minimum to enable the data inputed to the computer to meet regression requirements. When the replicates were combined, to yield 14 observations, the requirements were met by submitting two copies for each observation, for a total of 28 observations.

The situation becomes one of two many variables measured for the significantly fewer number of observations. The methodology employed to result in final regression equations, with accurate regression statistics, was to:

(1) obtain initial stepwise regression results by duplicating the seven original observations as described above, and

(2) then, using only the seven original observations, or the 14 obtained from replicate one combined with replicate two, to run regular multiple linear regressions with only the first three, or four of the independent variables which entered the stepwise regression as being primarily important in explaining the variance.

It is believed that the duplication of observations will not affect the regression's choice of entering variables, but it does affect the regression statistics, and they are, therefore, erroneous. This method resulted in only five, at most, variables in all final regressions, therefore, meeting the regressions' requirements.

Another problem with all regressions contained in the analysis, was that there is a high degree of correlation among many of the independent variables. A correlation matrix showing the correlation between all independent variables is given in Table XXXV, printed on pages 80-81. When high correlations exist between any, or all of the independent, or explanatory variables, collinearity can result. Collinearity is a situation where the explanatory variables interfere with each other, and it is a pitfall of regression because it can cause spurious forecasts

TABLE XXXV

CORRELATION MATRIX SHOWING COLLINEARITY AMONG ALL INDEPENDENT VARIABLES

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	1.0000								
X_2	-.0775	1.0000							
X_3	-.7628	.0172	1.0000						
X_4	-.3969	-.3694	.7595	1.0000					
X_5	-.7564	.3389	.9262	.5751	1.0000				
X_6	-.7618	.1711	.8422	.5595	.8659	1.0000			
X_7	.1951	.3578	.3790	.3352	.3810	.3052	1.0000		
X_8	-.3255	-.3516	.6899	.8892	.4372	.3475	.4029	1.0000	
X_9	-.1424	-.5579	-.0408	-.2165	-.2586	-.0269	-.3387	-.0925	1.0000
X_{10}	.3734	.0987	-.6000	-.6491	-.6455	-.7172	-.1748	-.2461	.2778
X_{11}	-.4212	-.5652	.5828	.7560	.2578	.3101	.1167	.9035	.2747
X_{12}	-.5778	-.4110	.4242	.1572	.1807	.2414	-.2147	.3732	.7791
X_{13}	-.4793	-.5355	.6003	.6494	.4302	.2284	-.2107	.5923	.1194
X_{14}	.0688	.1438	.4041	.1668	.3250	.3413	.8366	.2894	.2090
X_{15}	.0964	.3390	.2209	-.0296	.1551	.0222	.7273	.3162	.0823
X_{16}	.2621	.4403	-.0637	-.3017	-.0668	-.2715	.5558	.0894	.0070
X_{17}	.5817	.4143	-.3440	-.5772	-.2487	-.4002	.4855	-.3681	.0546

TABLE XXXV (continued)

CORRELATION MATRIX SHOWING COLLINEARITY AMONG ALL INDEPENDENT VARIABLES

	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}
x_{10}	1.0000							
x_{11}	-.0909	1.0000						
x_{12}	.2200	.6565	1.0000					
x_{13}	-.4183	.5706	.4367	1.0000				
x_{14}	-.0533	.1847	.2153	-.1379	1.0000			
x_{15}	.4377	.2197	.2777	-.2410	.8005	1.0000		
x_{16}	.6688	-.0055	.1443	-.3616	.5899	.9341	1.0000	
x_{17}	.4880	-.4874	-.1795	-.4991	.5855	.6666	.7783	1.0000

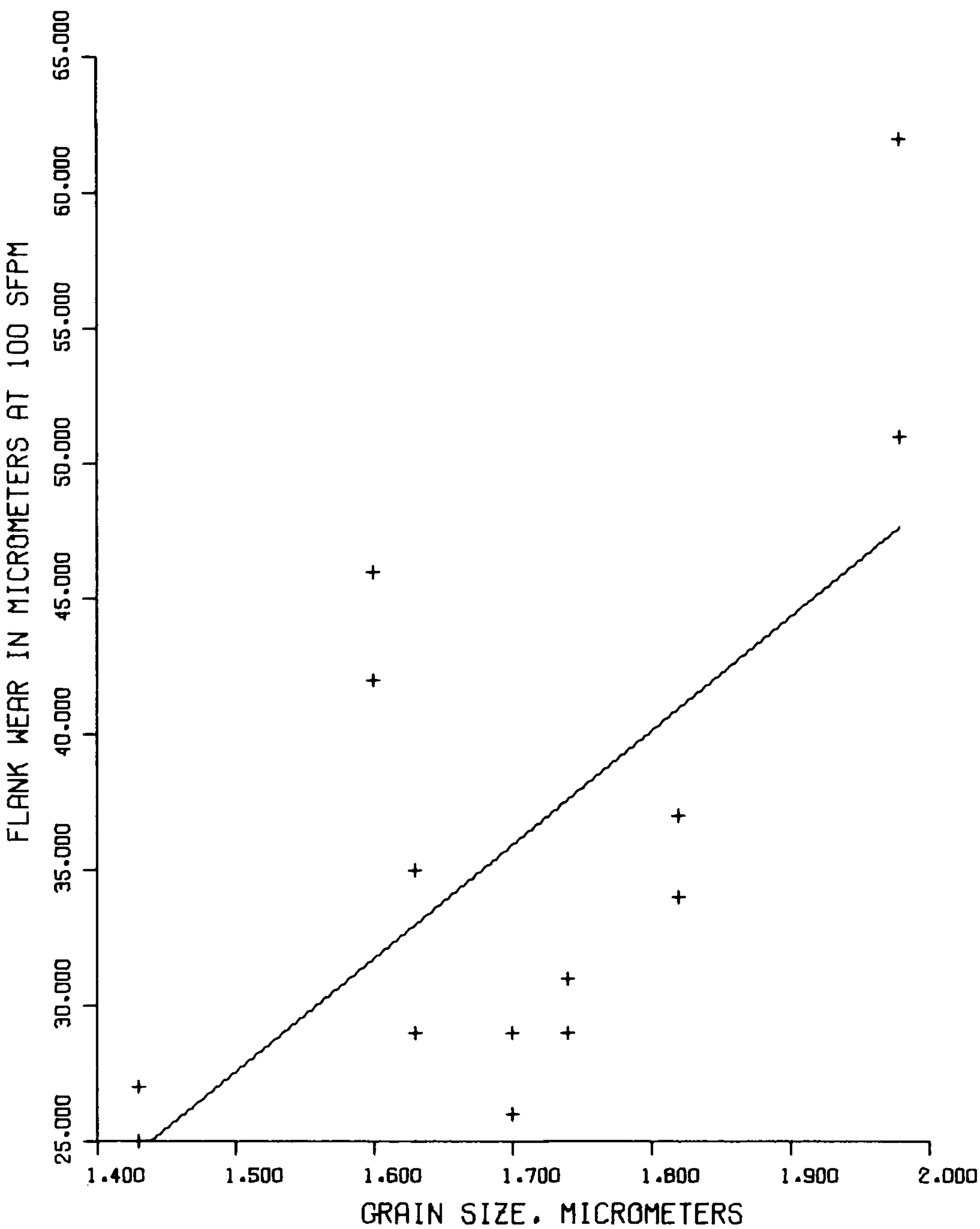
to be resulted from using the predicting equation. Collinearity can be recognized when the t-statistics of two seemingly important explanatory variables are low. Often, collinearity causes the estimated coefficients of explanatory variables to have the opposite sign from what would logically be expected, or from what would be indicated by the variable's partial correlation with the dependent variable.

Collinearity was definitely a problem in the regressions performed for this research. Many times the t-statistics for two of the three, or four explanatory variables were low, and often the signs of the coefficients were reversed from the signs of the variables' partial correlations with the dependent variables. There are methods which can sometimes reduce collinearity, but they are not applicable in this case, by virtue of the nature of the independent variables used in attempting to correlate properties with performance. It should be noted that the arrows shown in all tables defining regression results, indicate the sign of the variable's coefficient, and not the sign of the variable's partial correlation with the dependent variable. The sign of the partial correlation would be a better indicator of an independent variable's general relationship with the dependent variable, but the signs of the variables' coefficients indicate the effect of the variables on the dependent variable in any specific equation.

The last observation to be made about the use of multiple linear regression equations to define the correlation of properties and performance of tungsten carbide is that, by using this method, one is limited to linear relationships for each of the independent variables versus the dependent variable for each condition. The question which naturally arises is, does each of the independent variables have a linear relationship with the dependent variables? To view the relationships of all independent variables versus the dependent variables, scatter plots were drawn using the data from replicate one and the data from replicate two. Thus, 14 wear values are plotted with the seven values of the independent property measurement for each condition, type of wear, and each independent property. The plots are shown in Figures 8 through 109, in order of property measurements corresponding with Table XXIX, for flank wear at the three conditions, and then for nose wear at the three conditions.

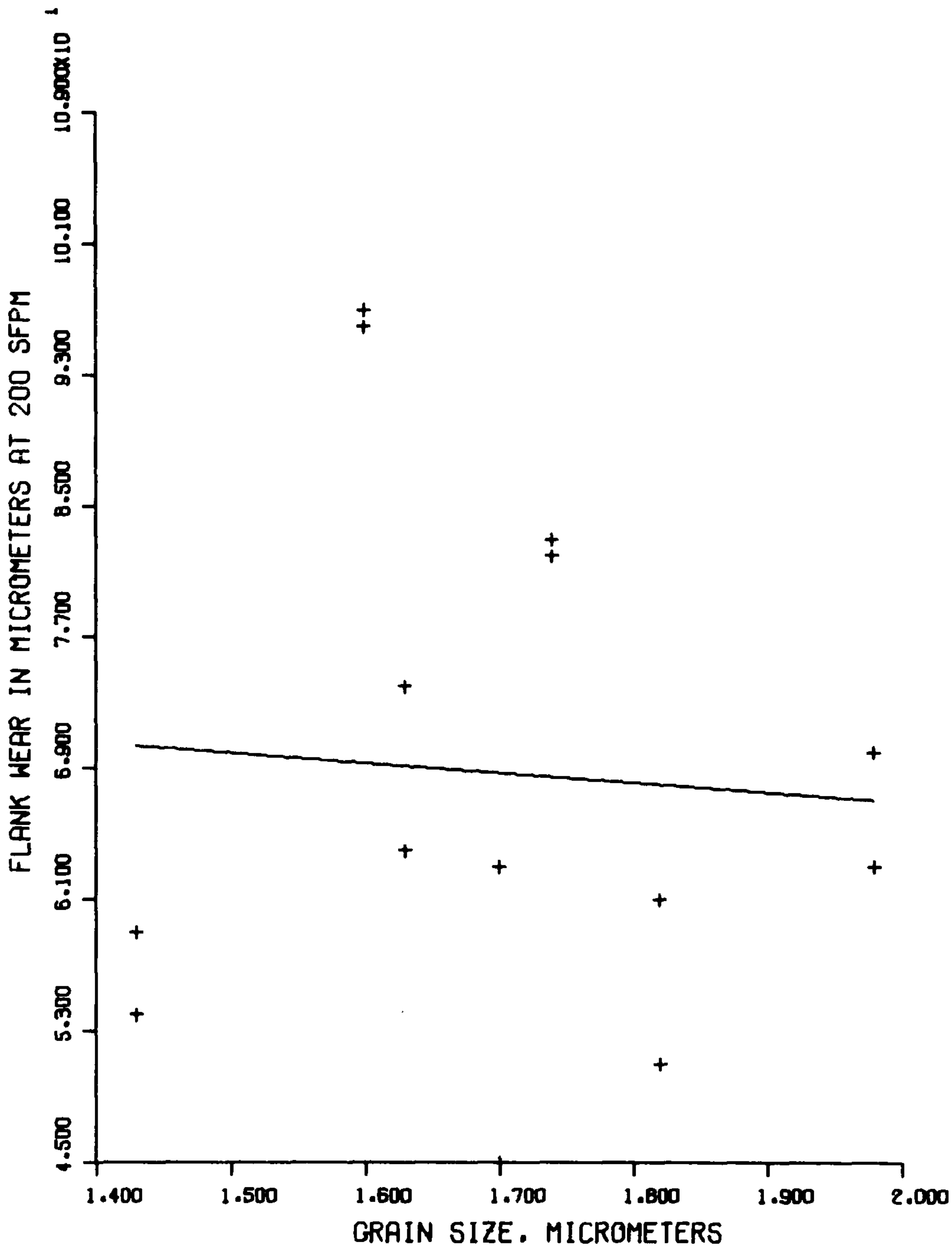
By examination of these plots, it is seen that the straight line generated by linear regression, for that independent property versus the dependent variable only, does not usually fit the scatter plot very accurately.

FIGURE 8



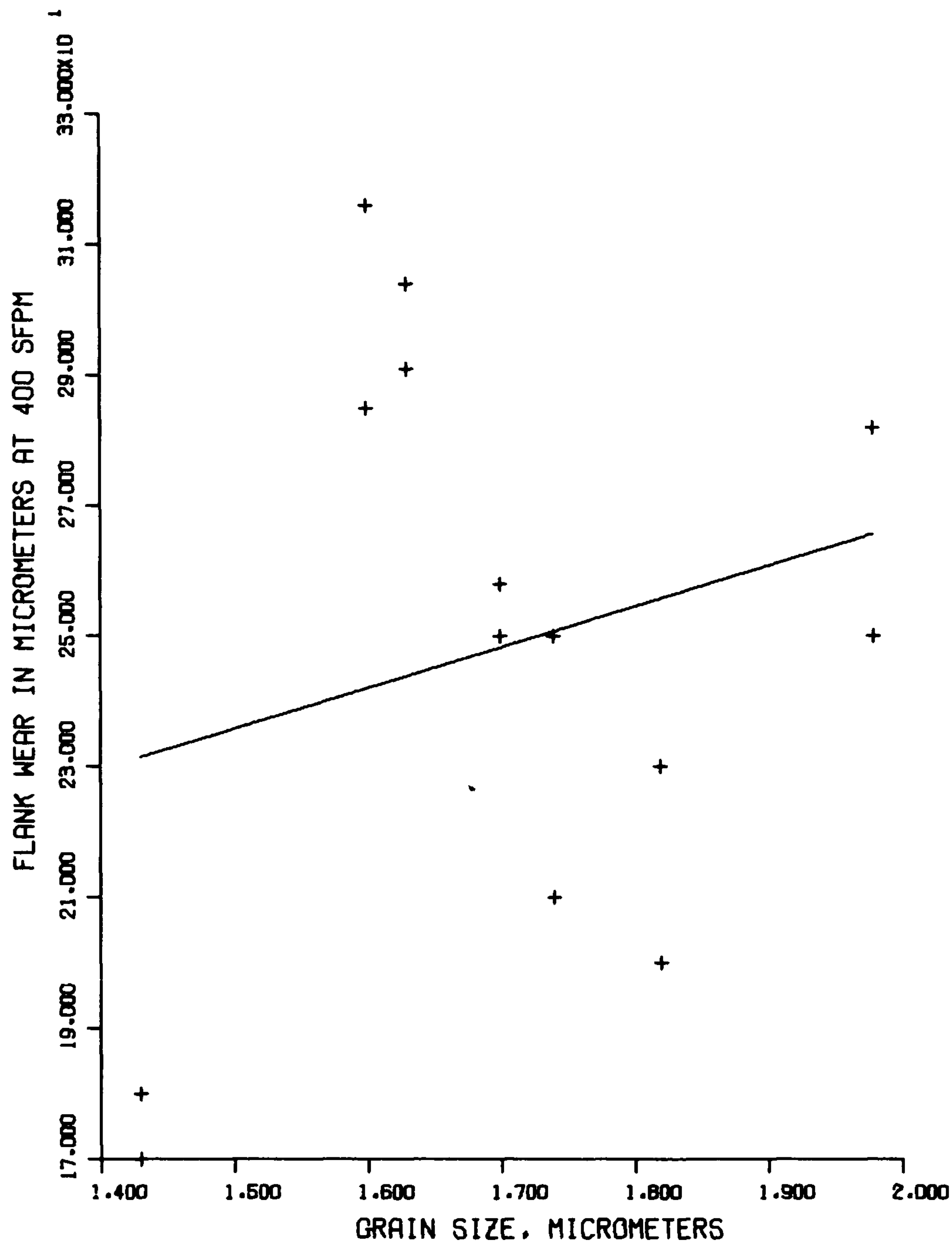
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 9



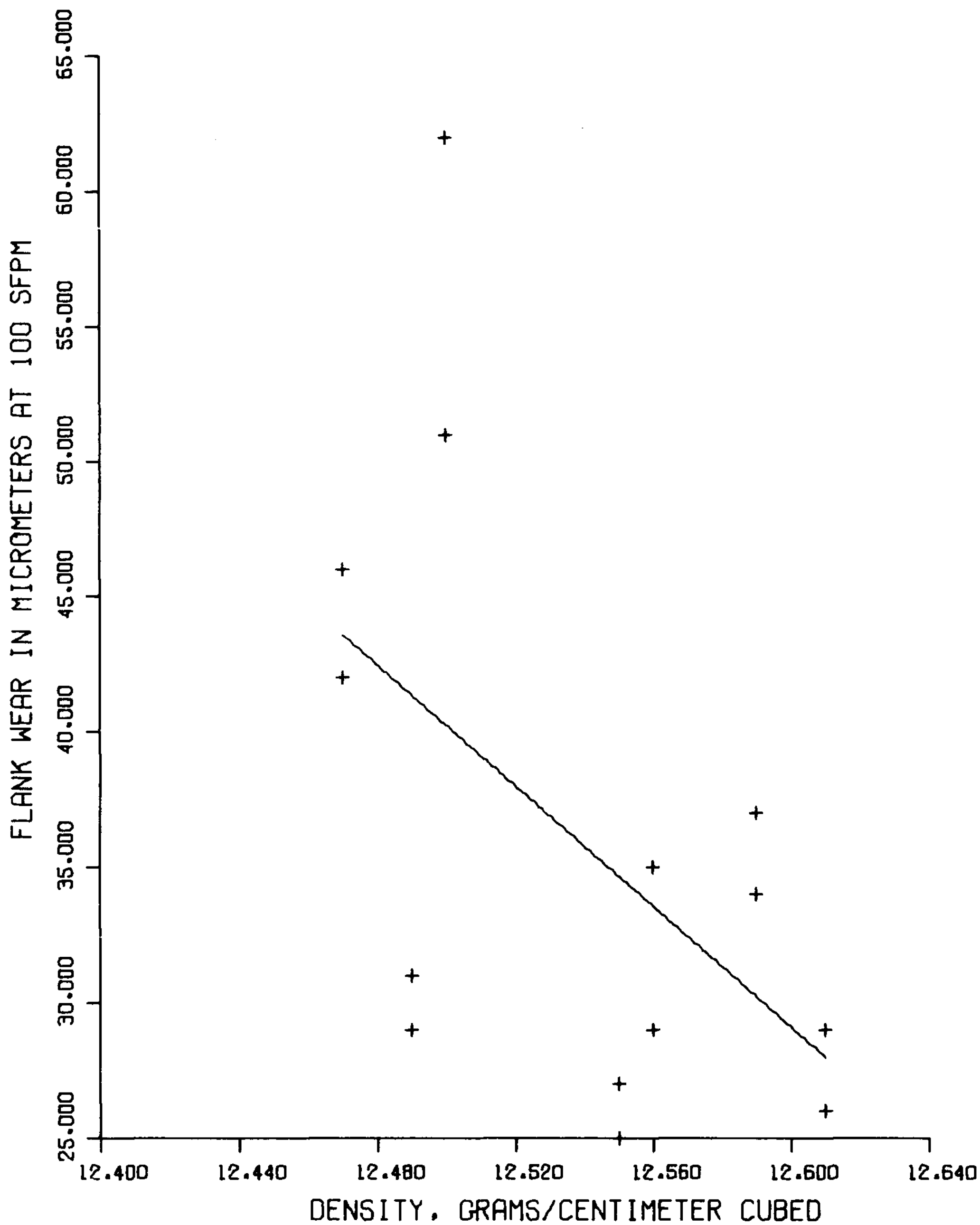
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 10



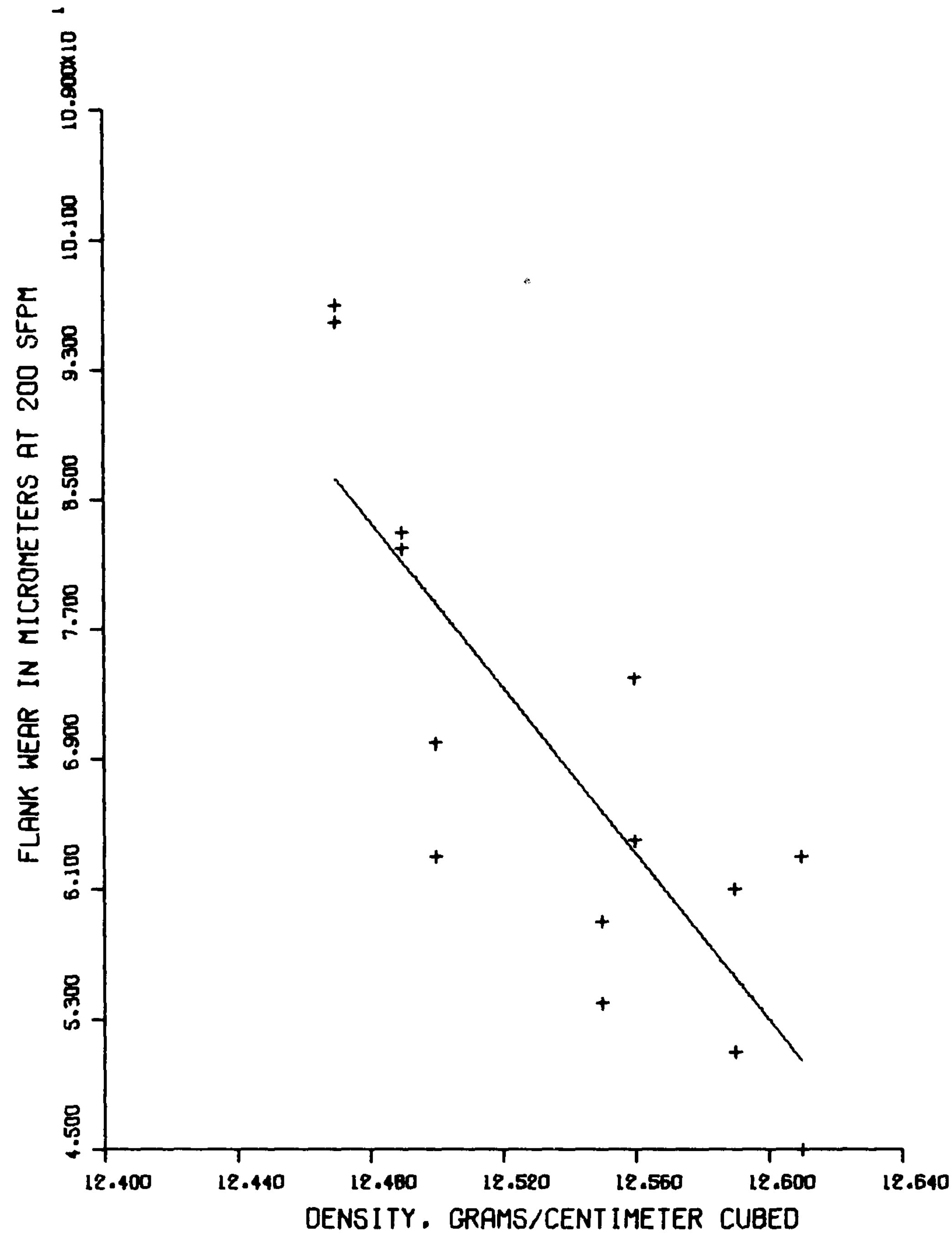
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 11



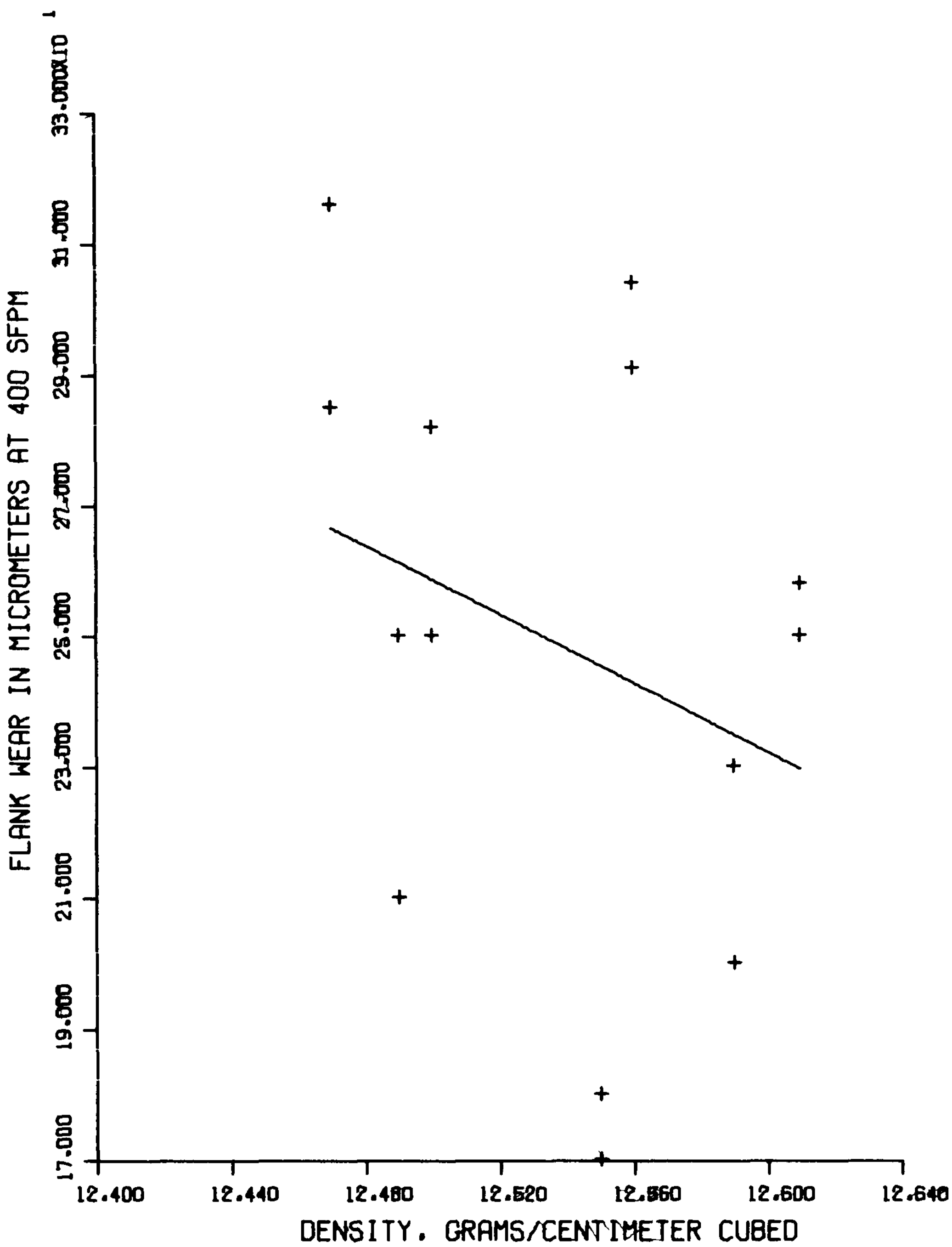
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 12



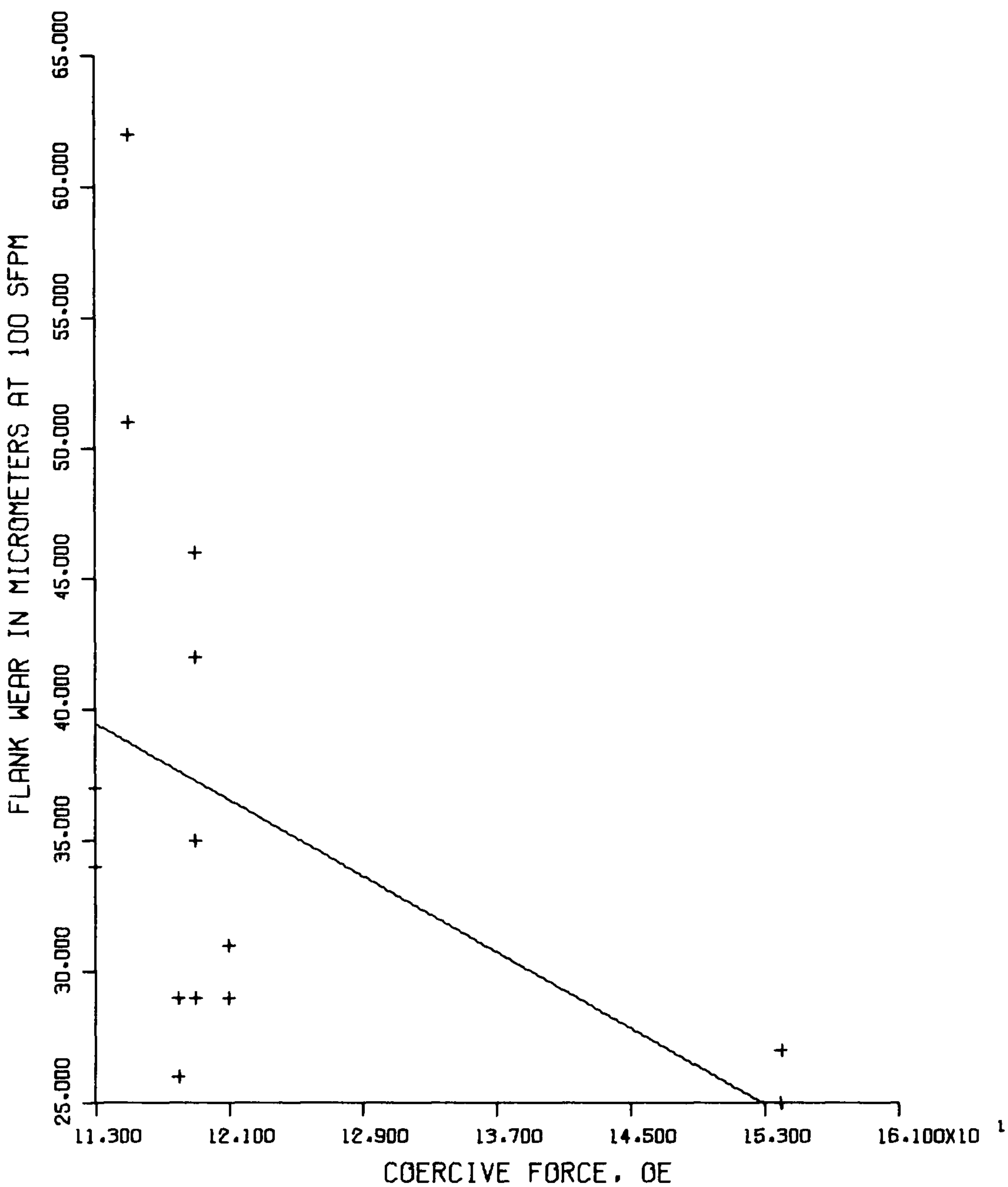
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 13



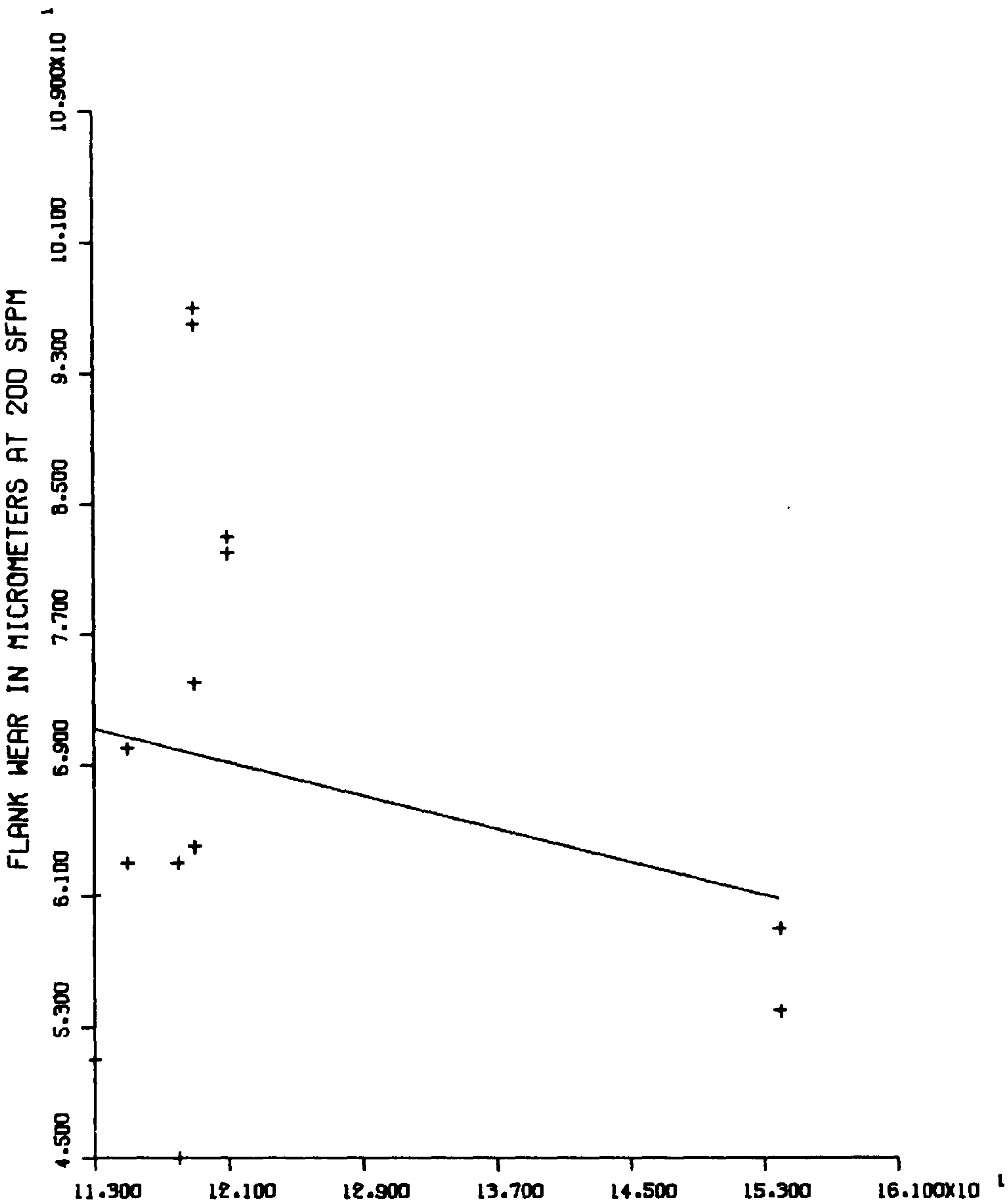
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 14



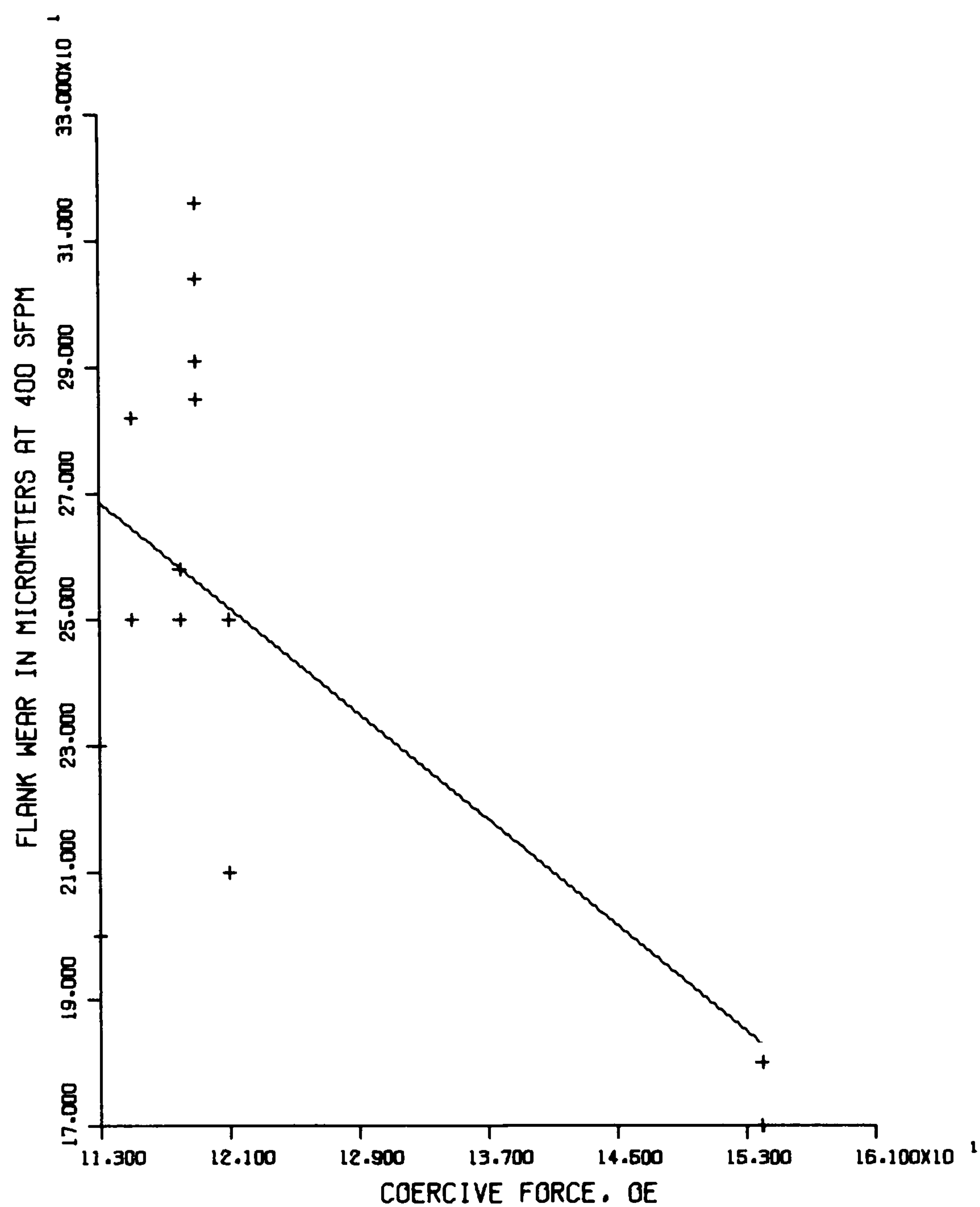
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 15



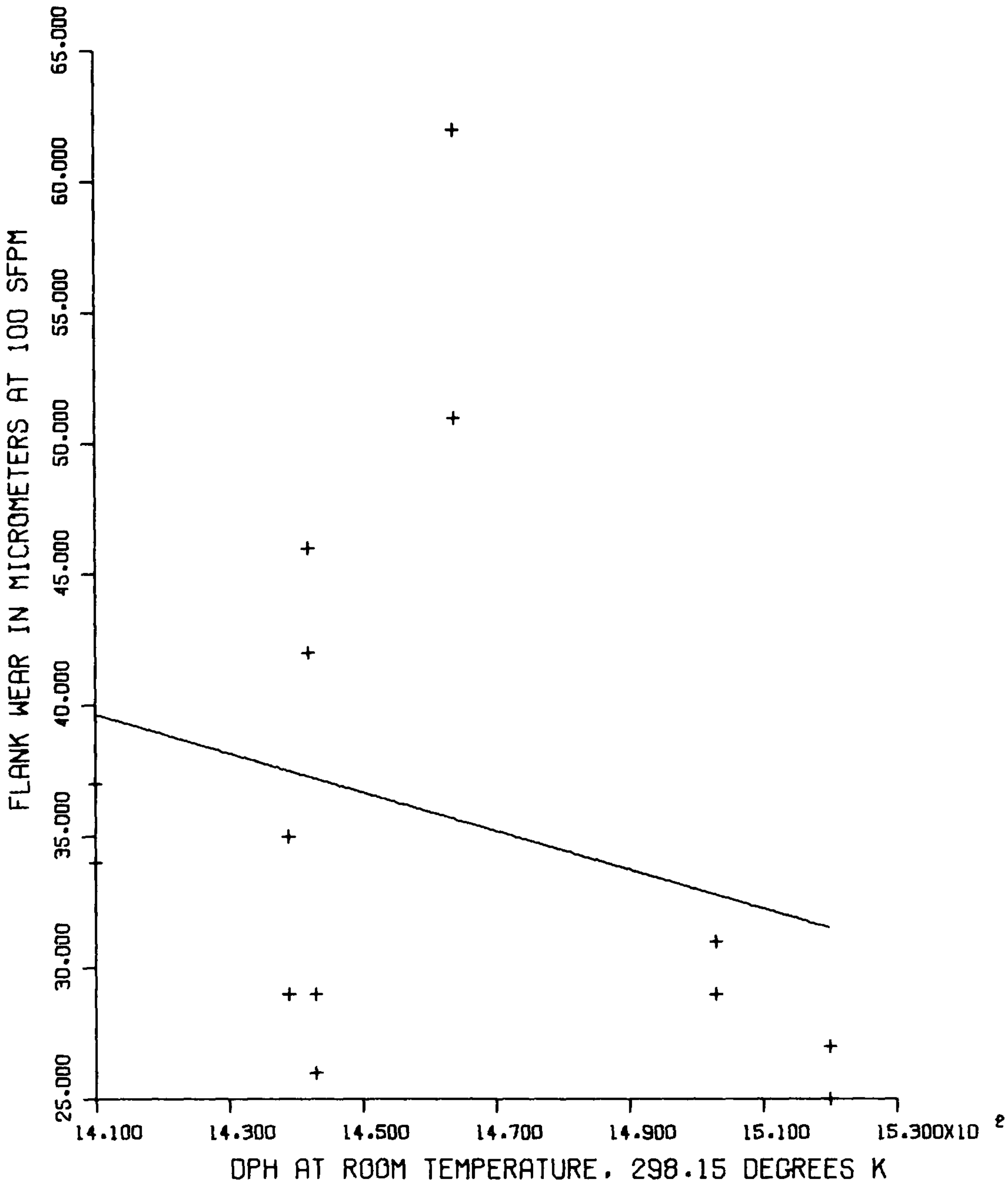
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 16



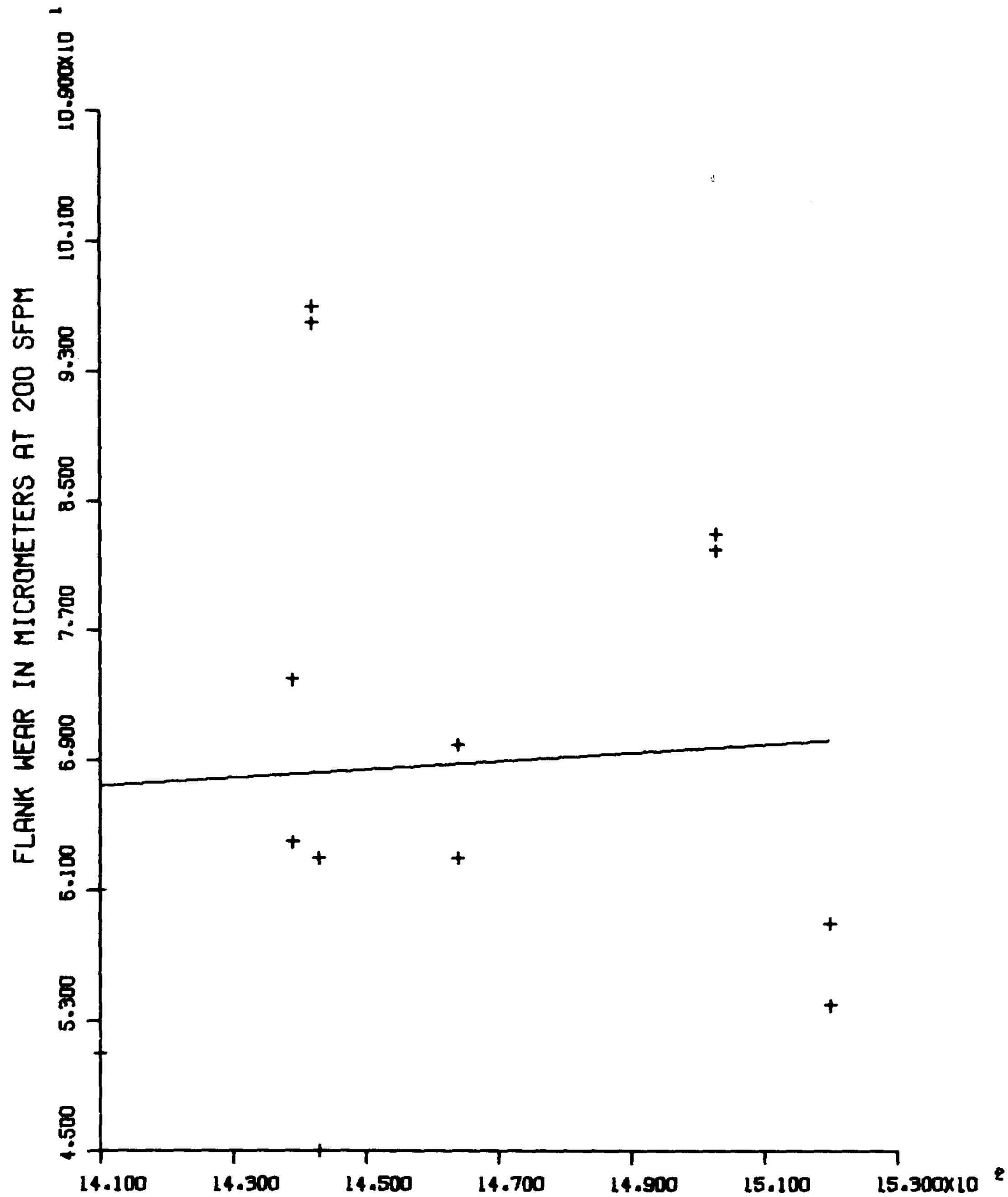
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 17



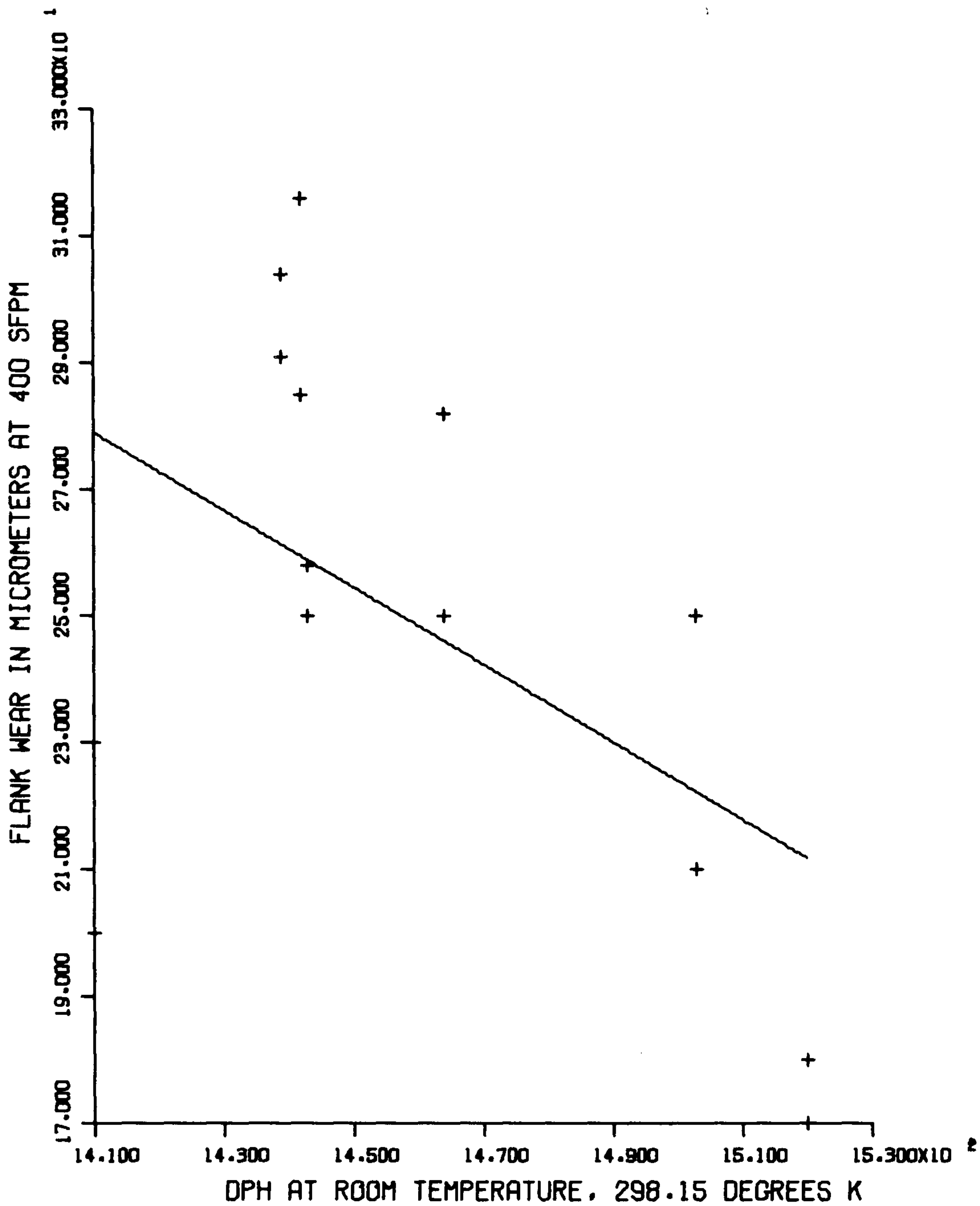
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 18



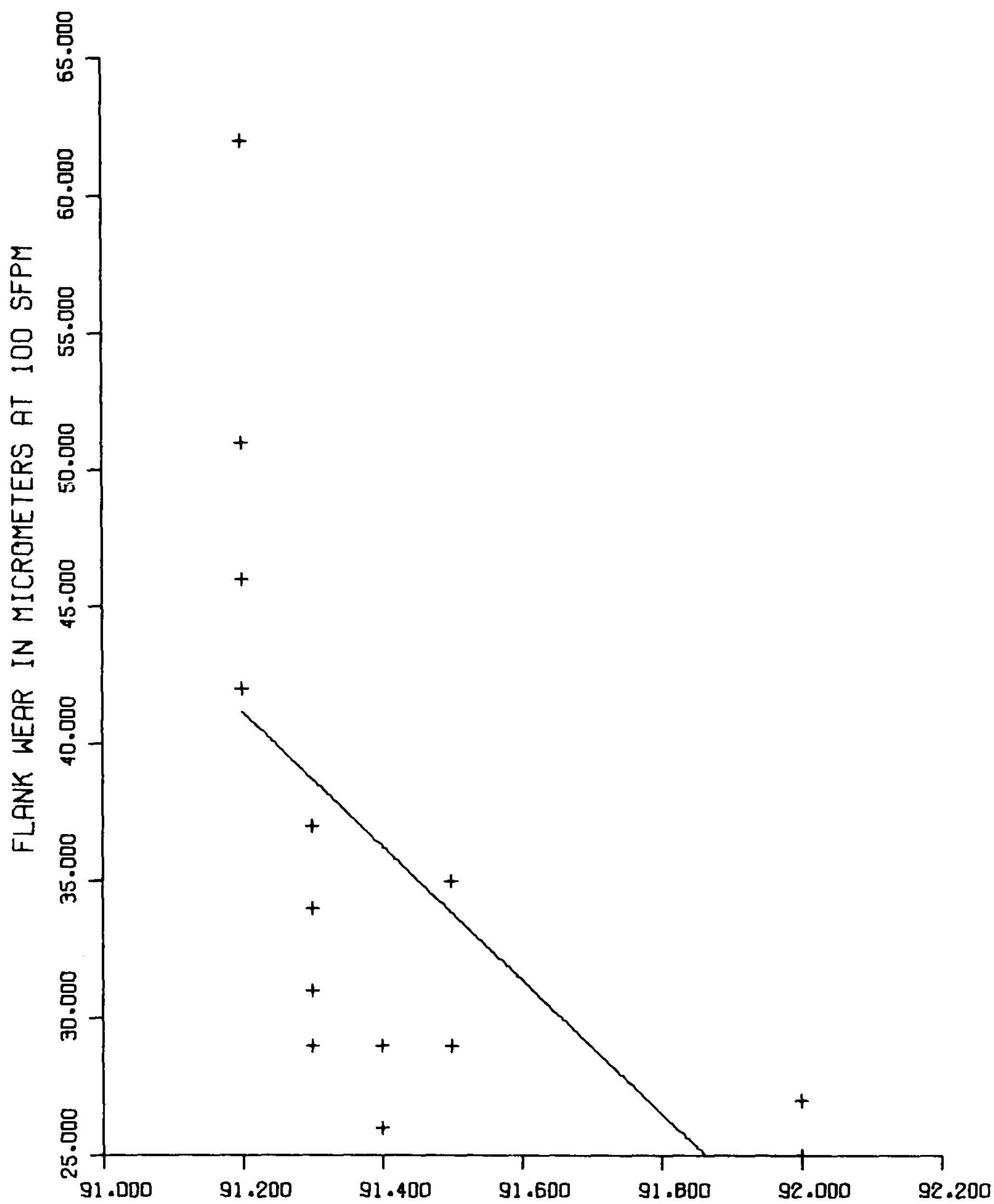
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 19



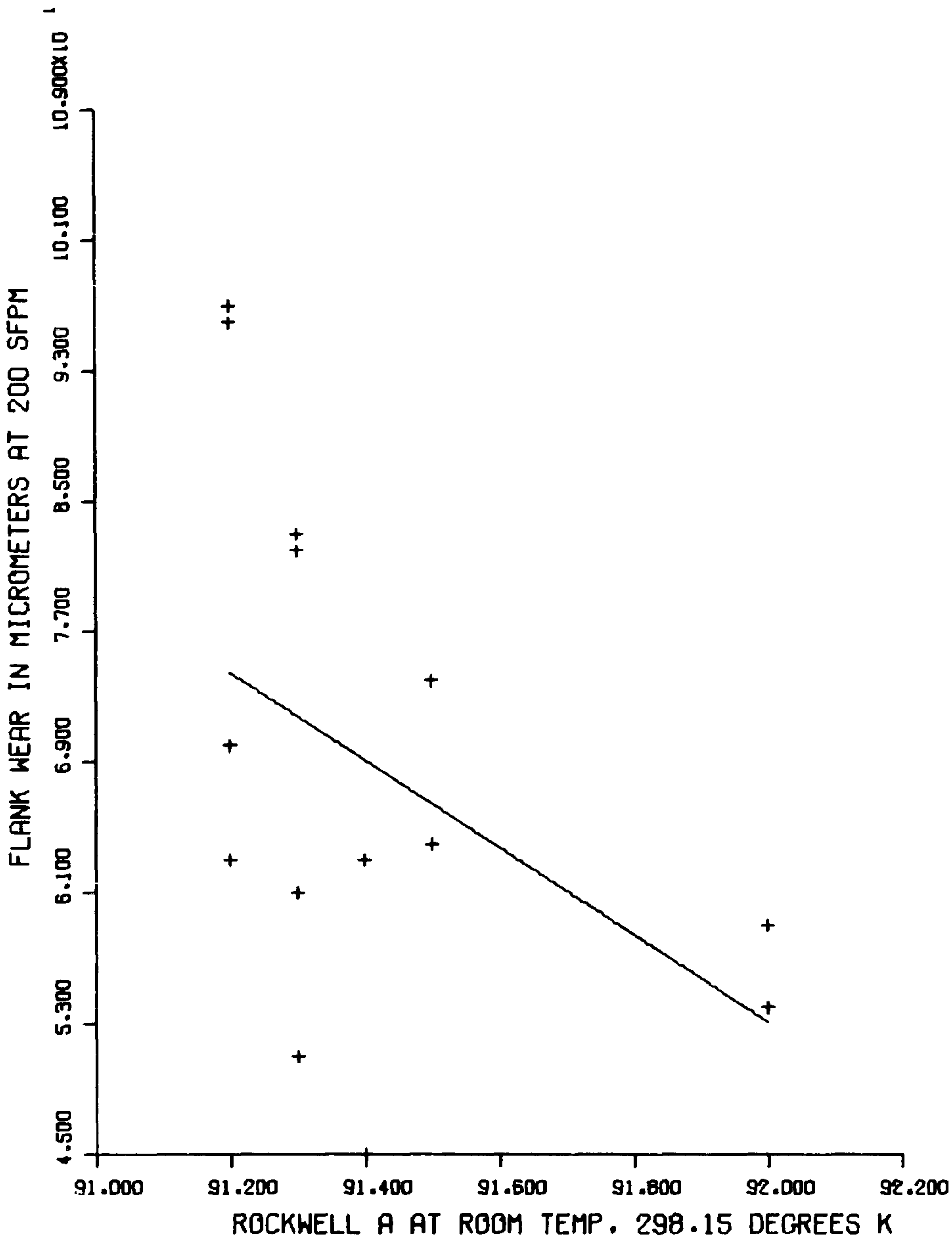
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 20



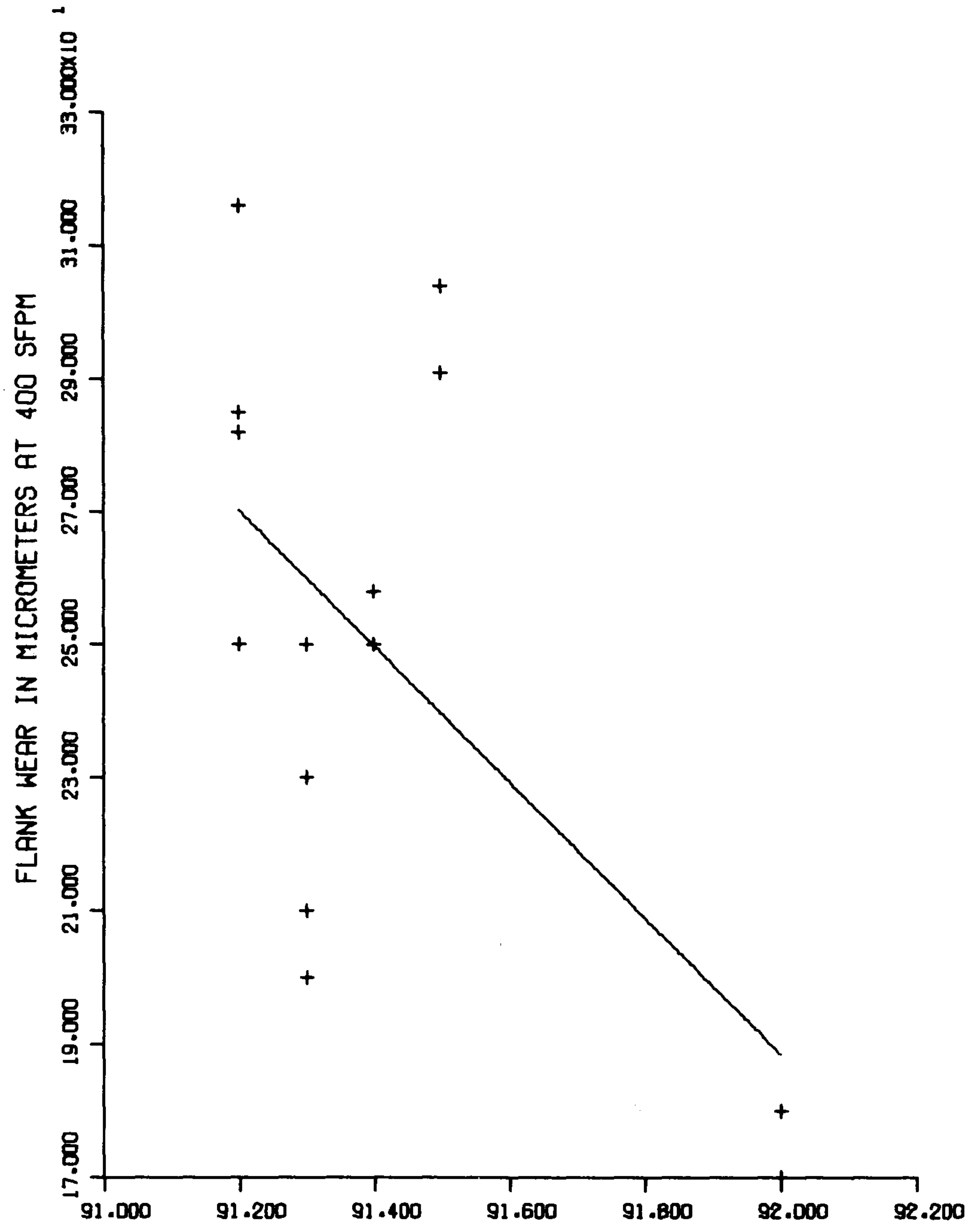
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 21



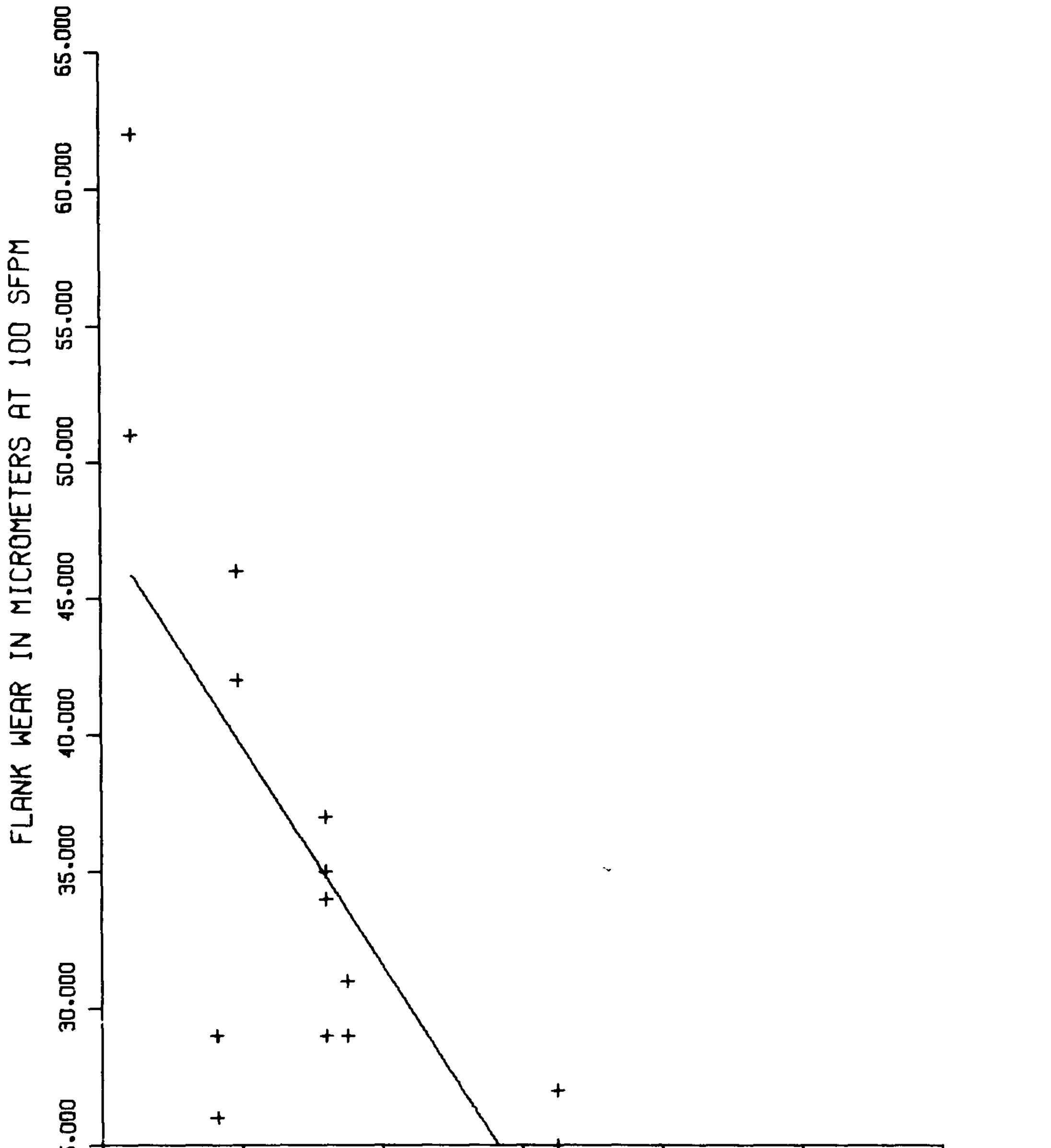
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 22



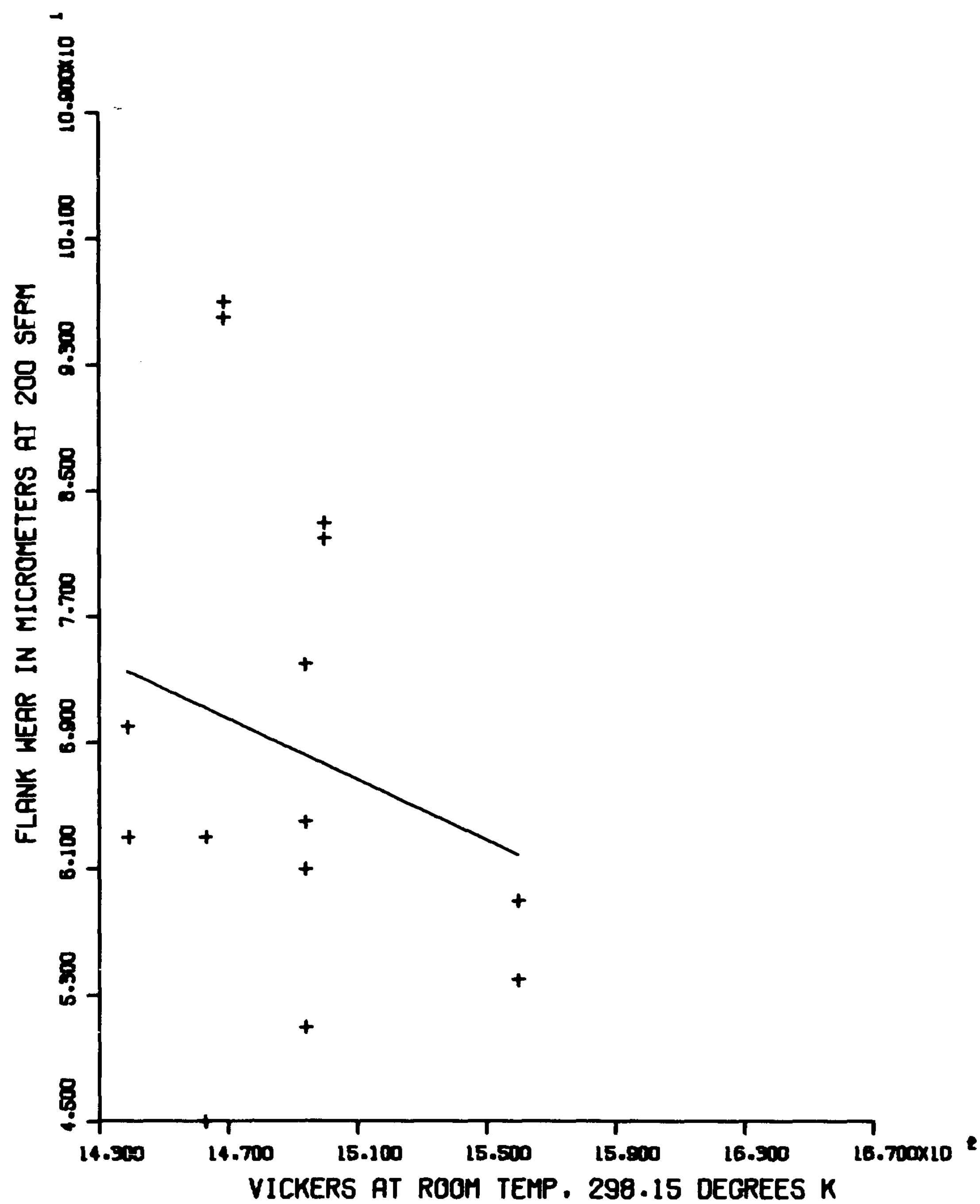
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 23



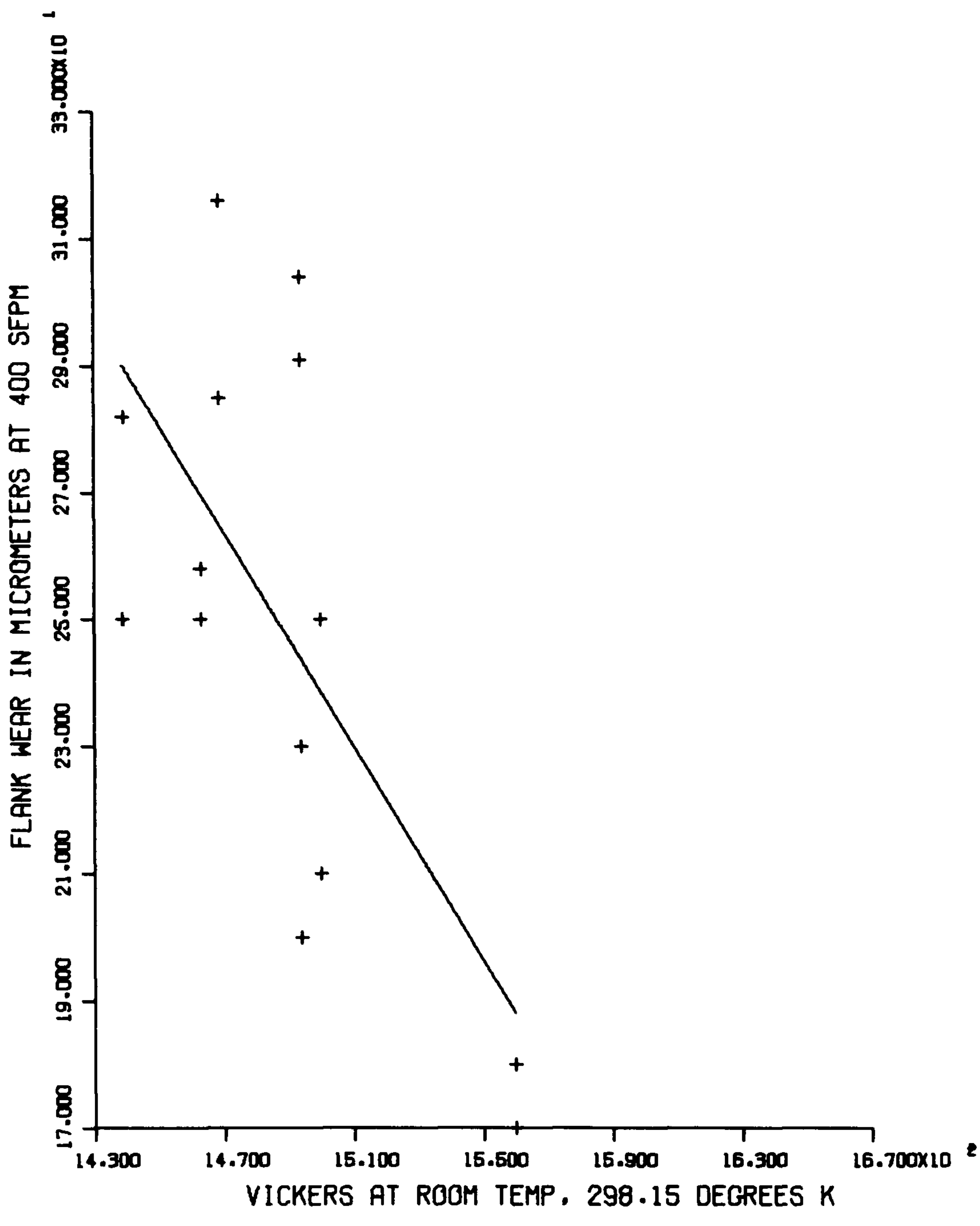
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 24



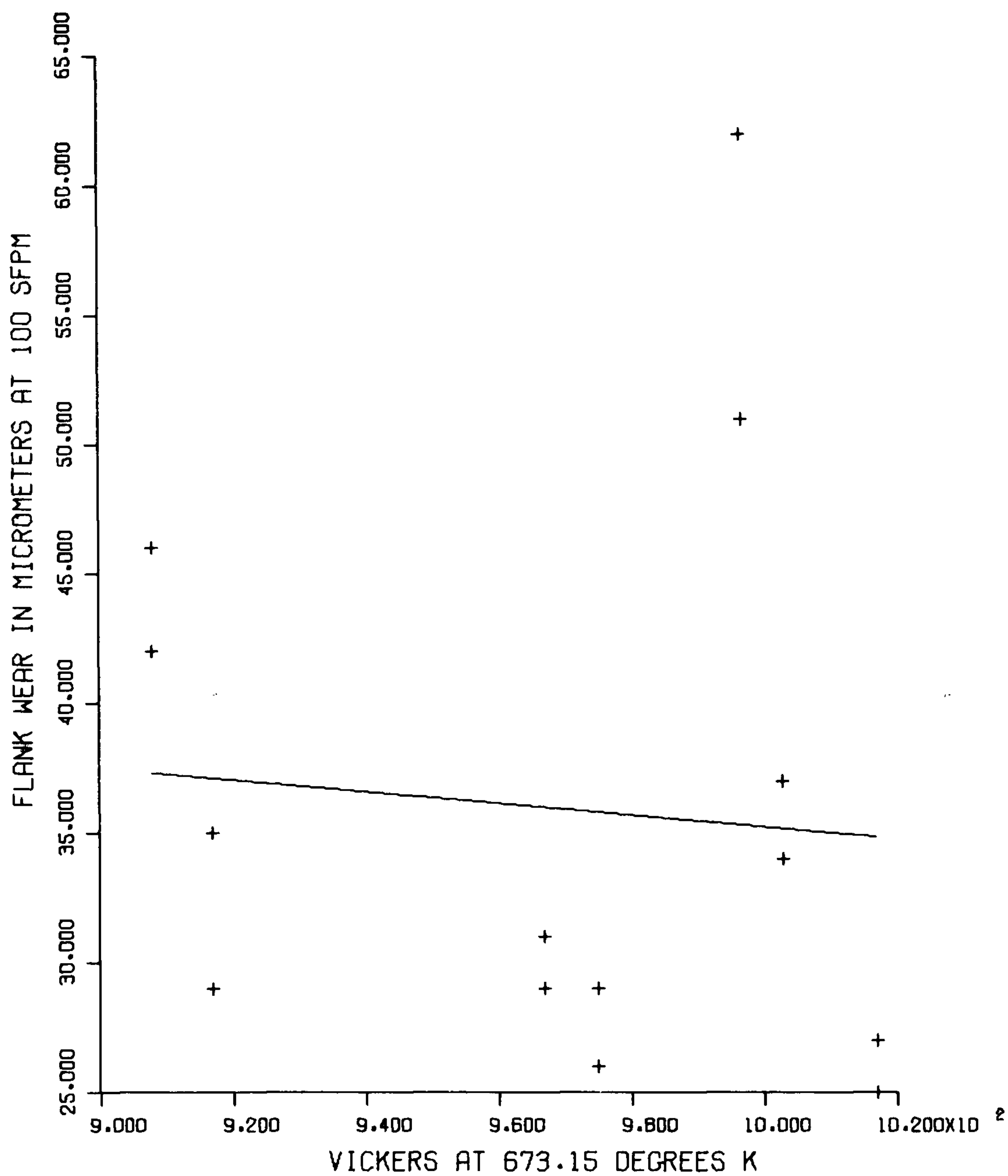
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 25



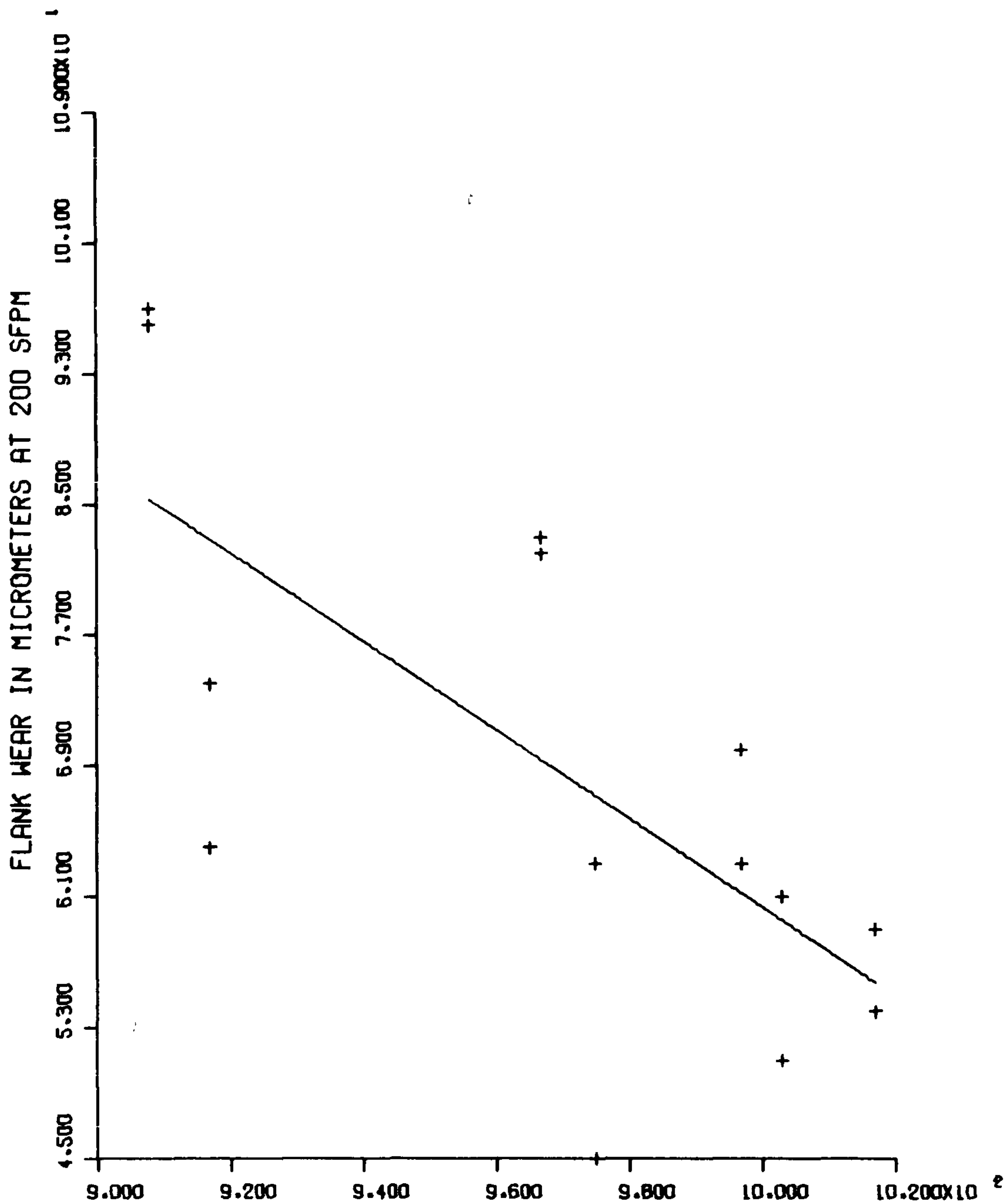
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 26



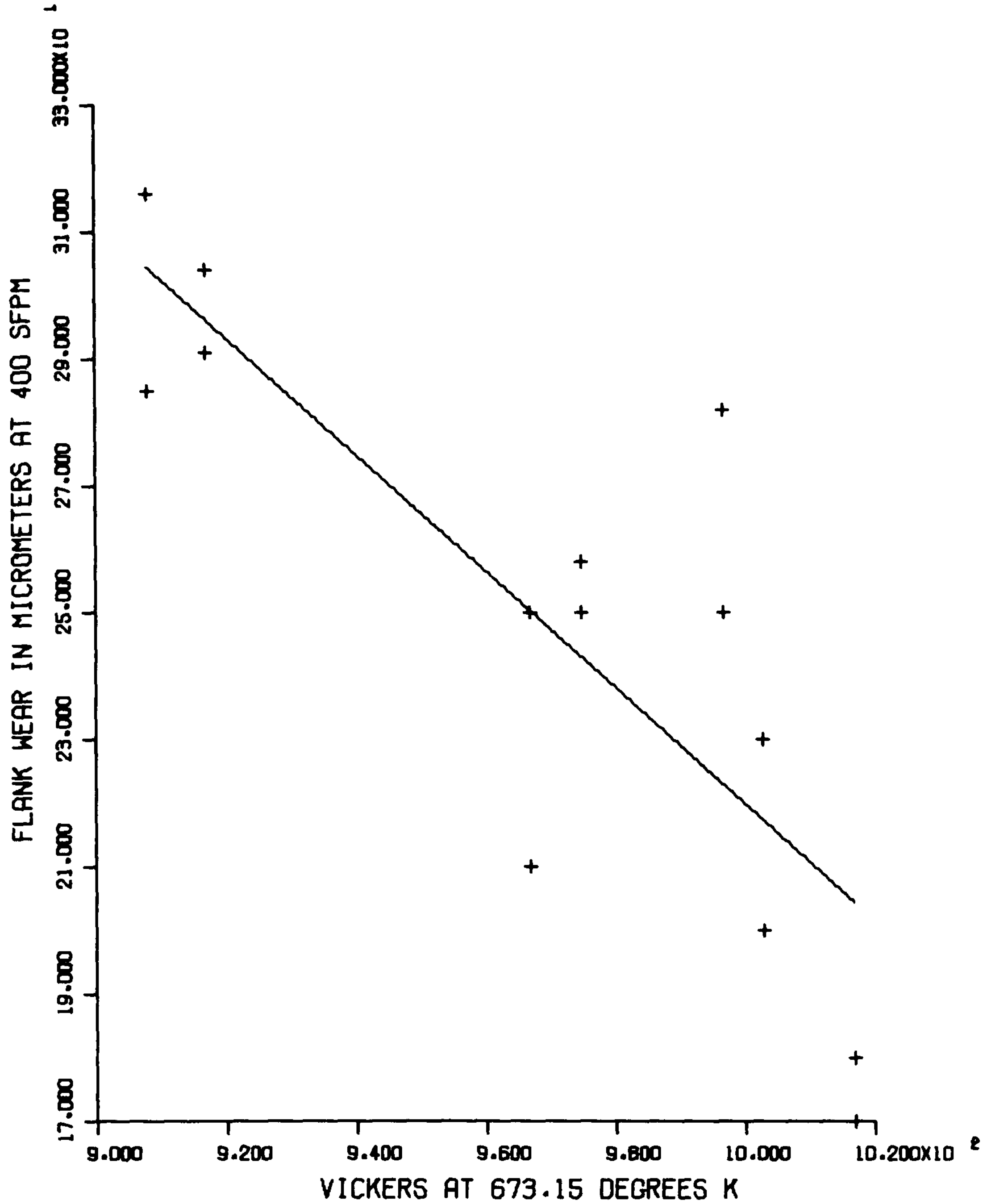
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 27



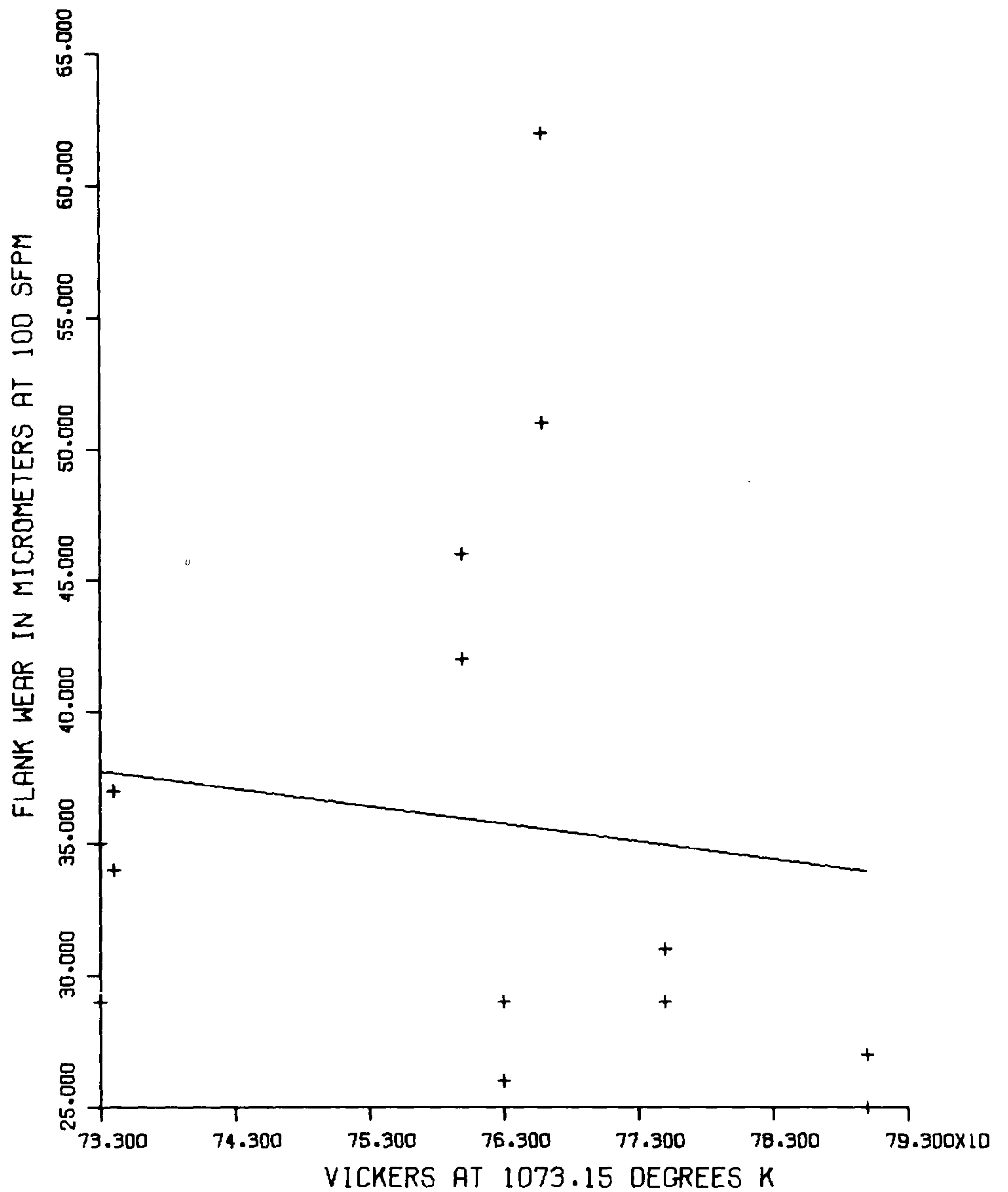
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 28



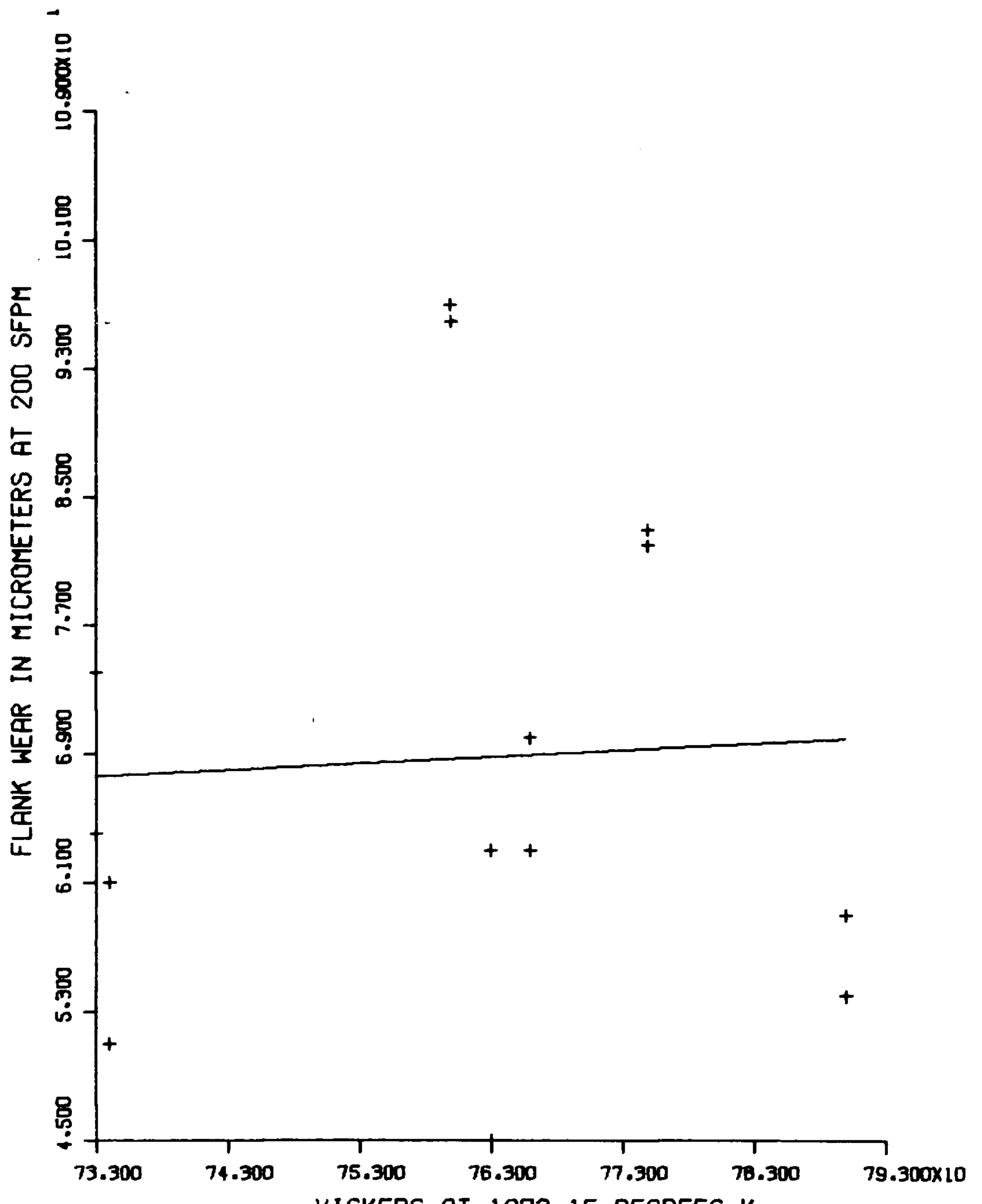
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 29



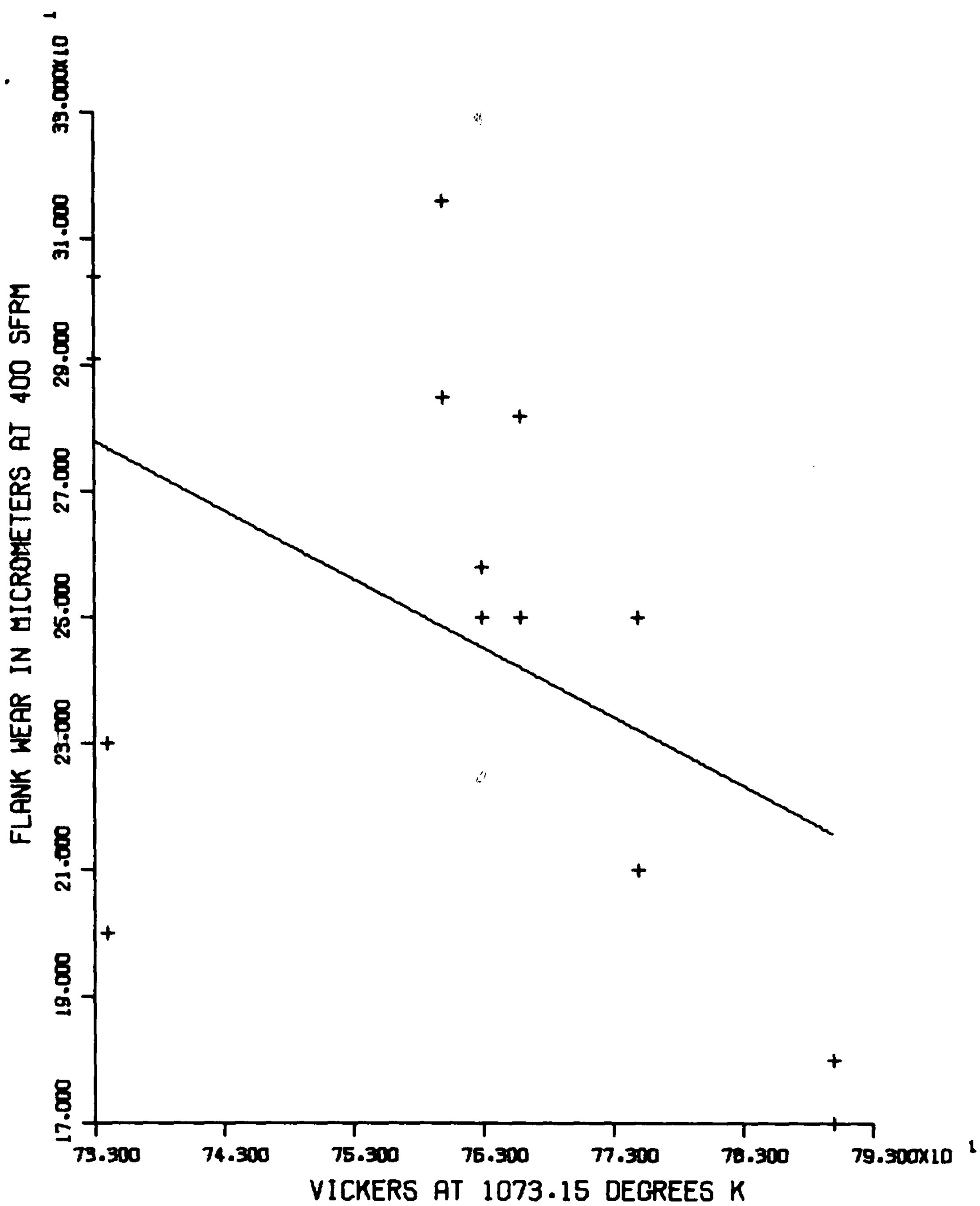
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 30



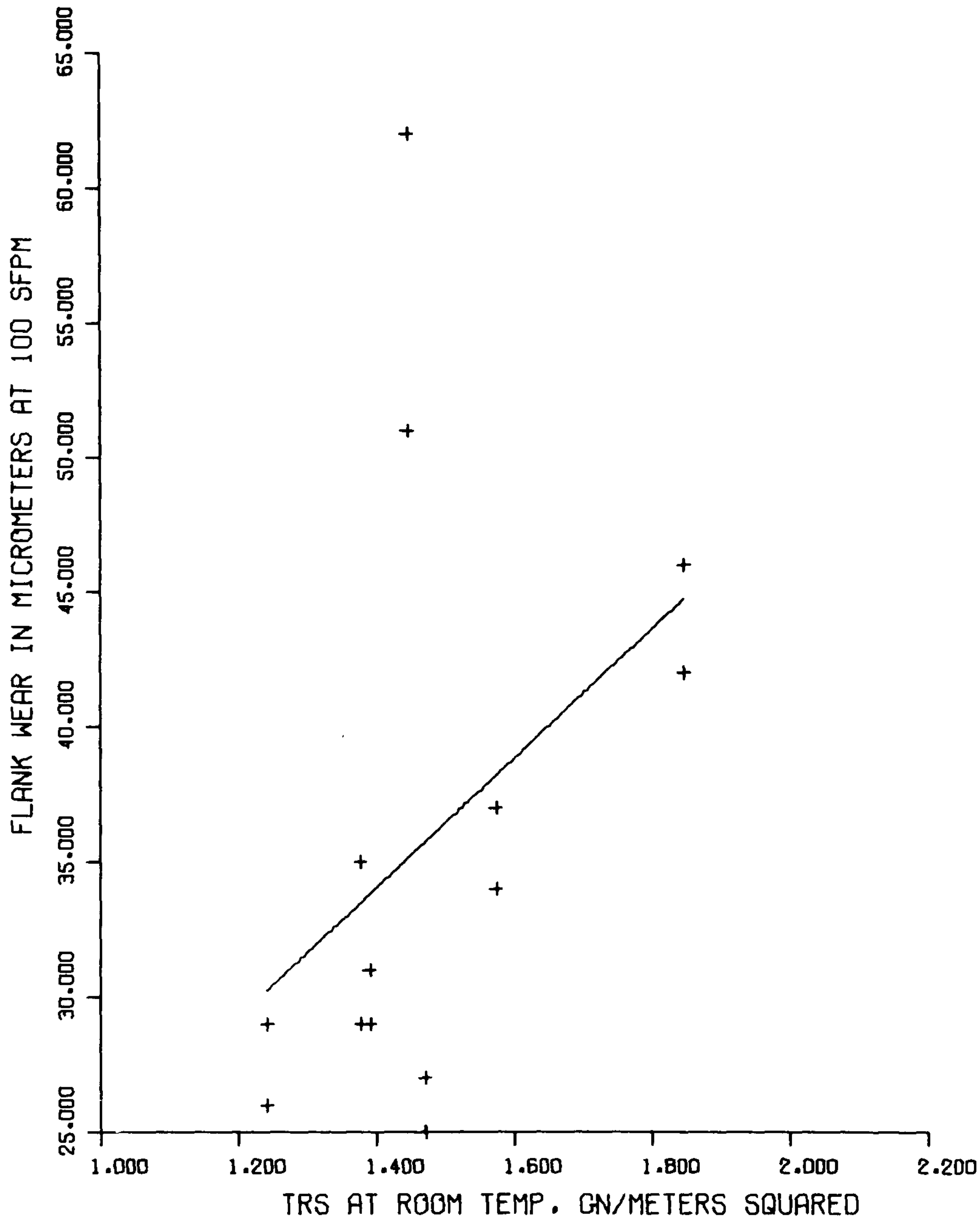
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 31



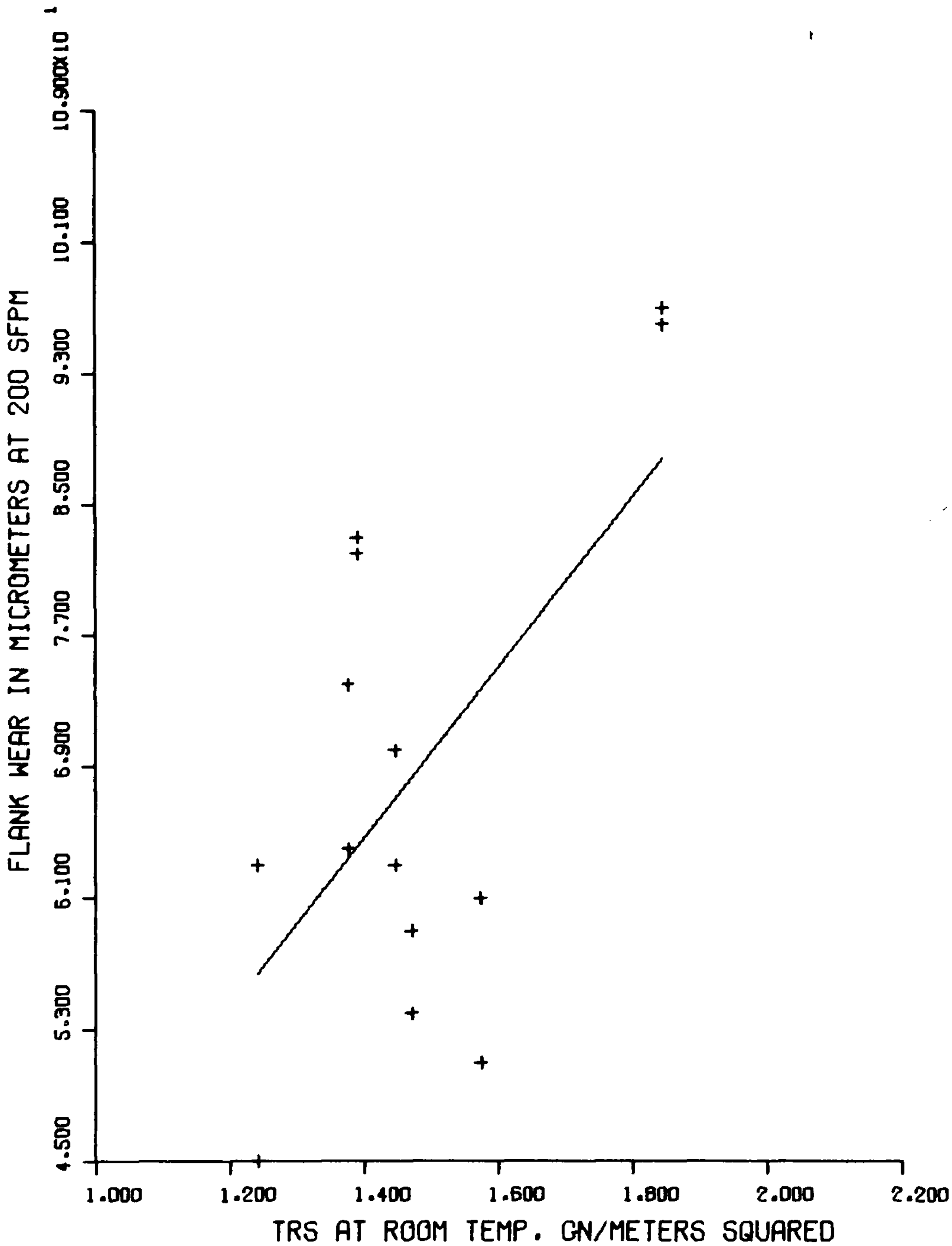
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 32



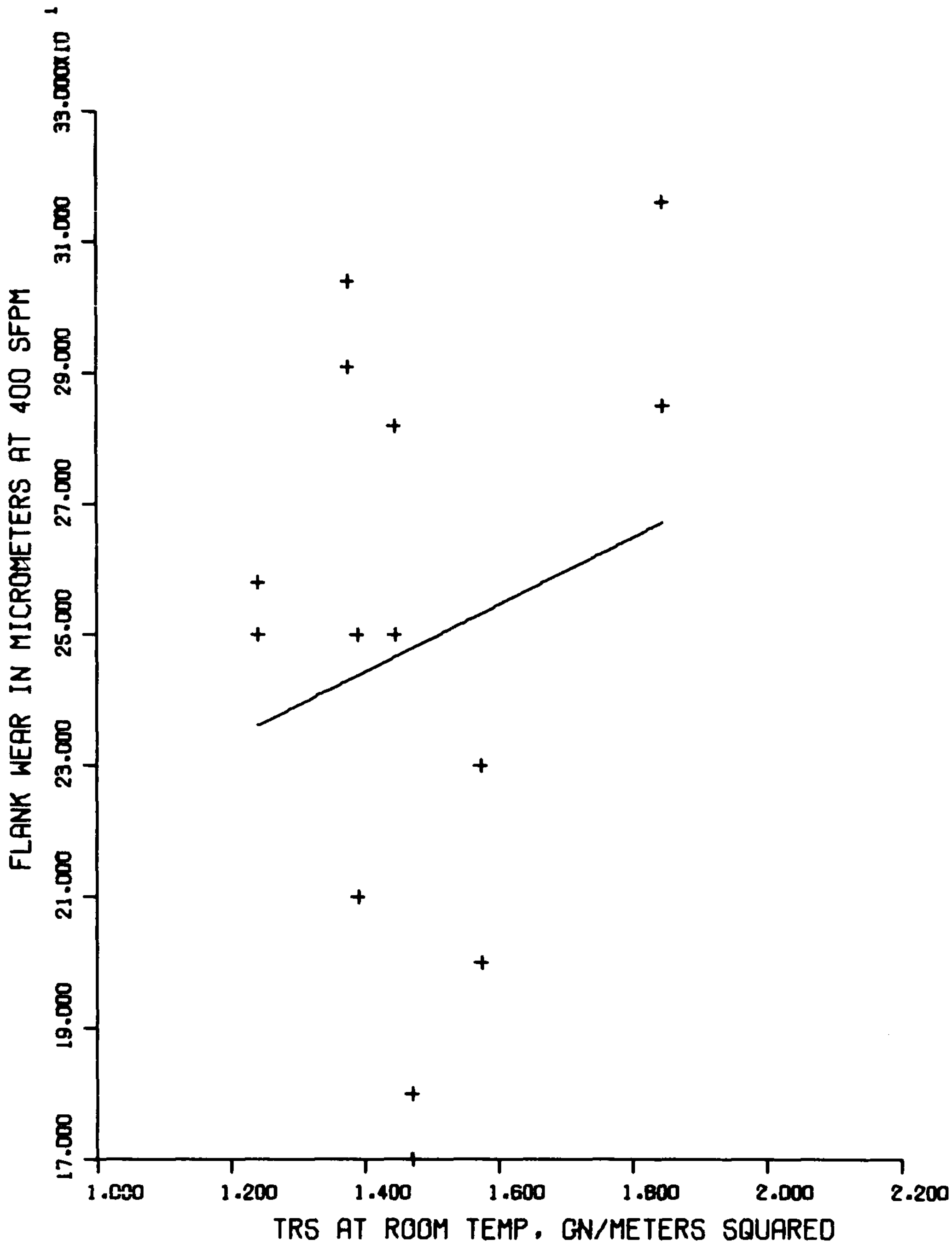
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 33



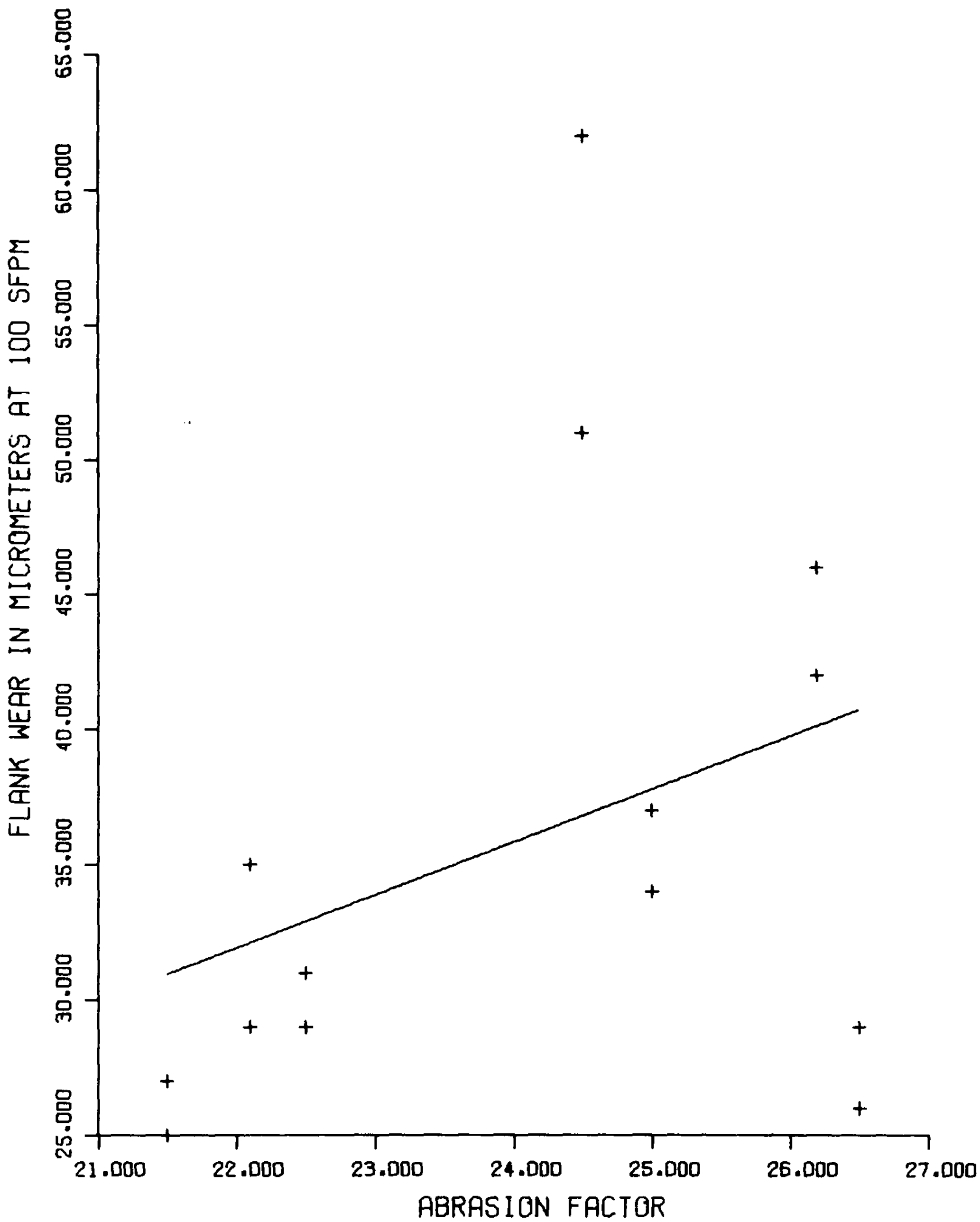
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 34



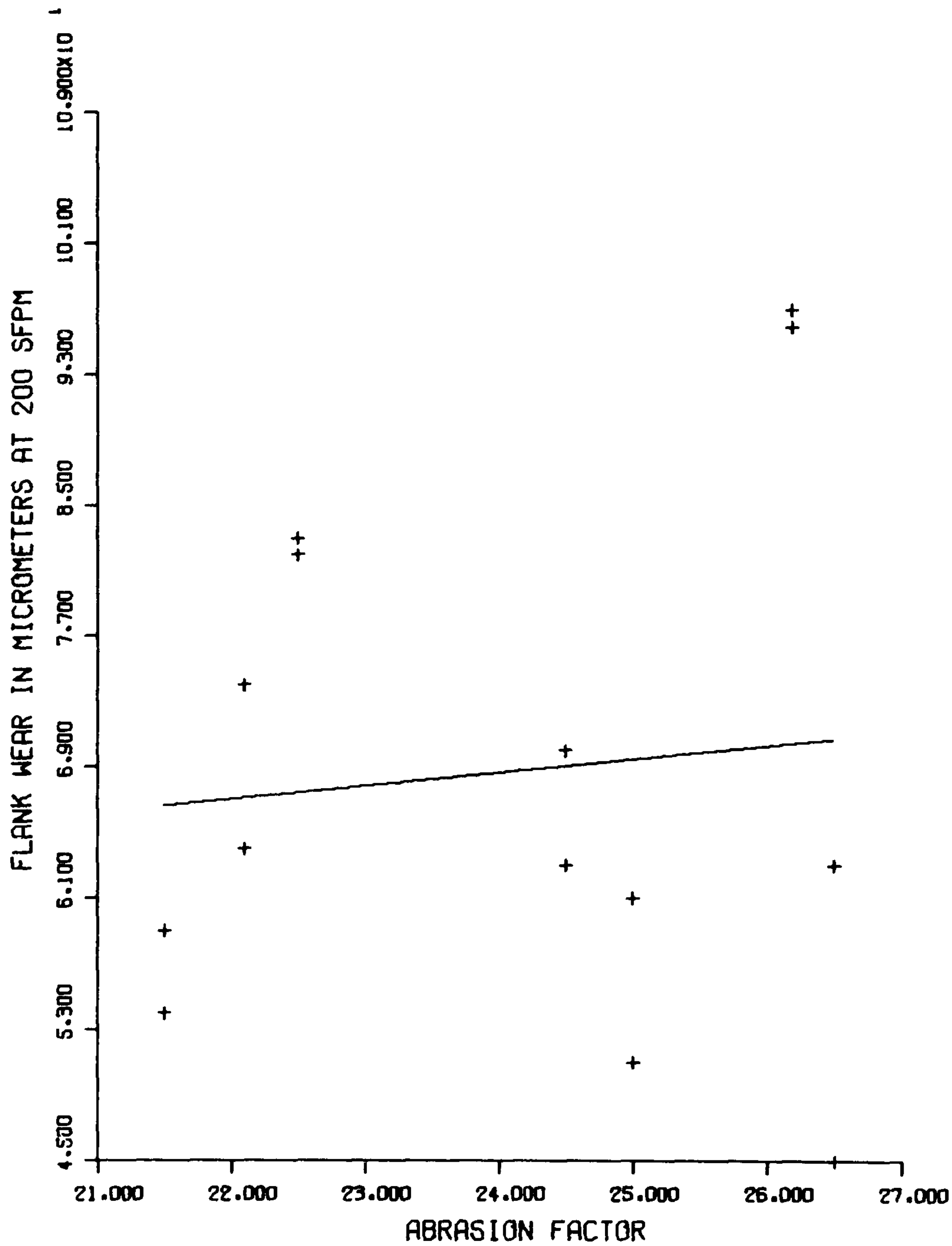
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 35



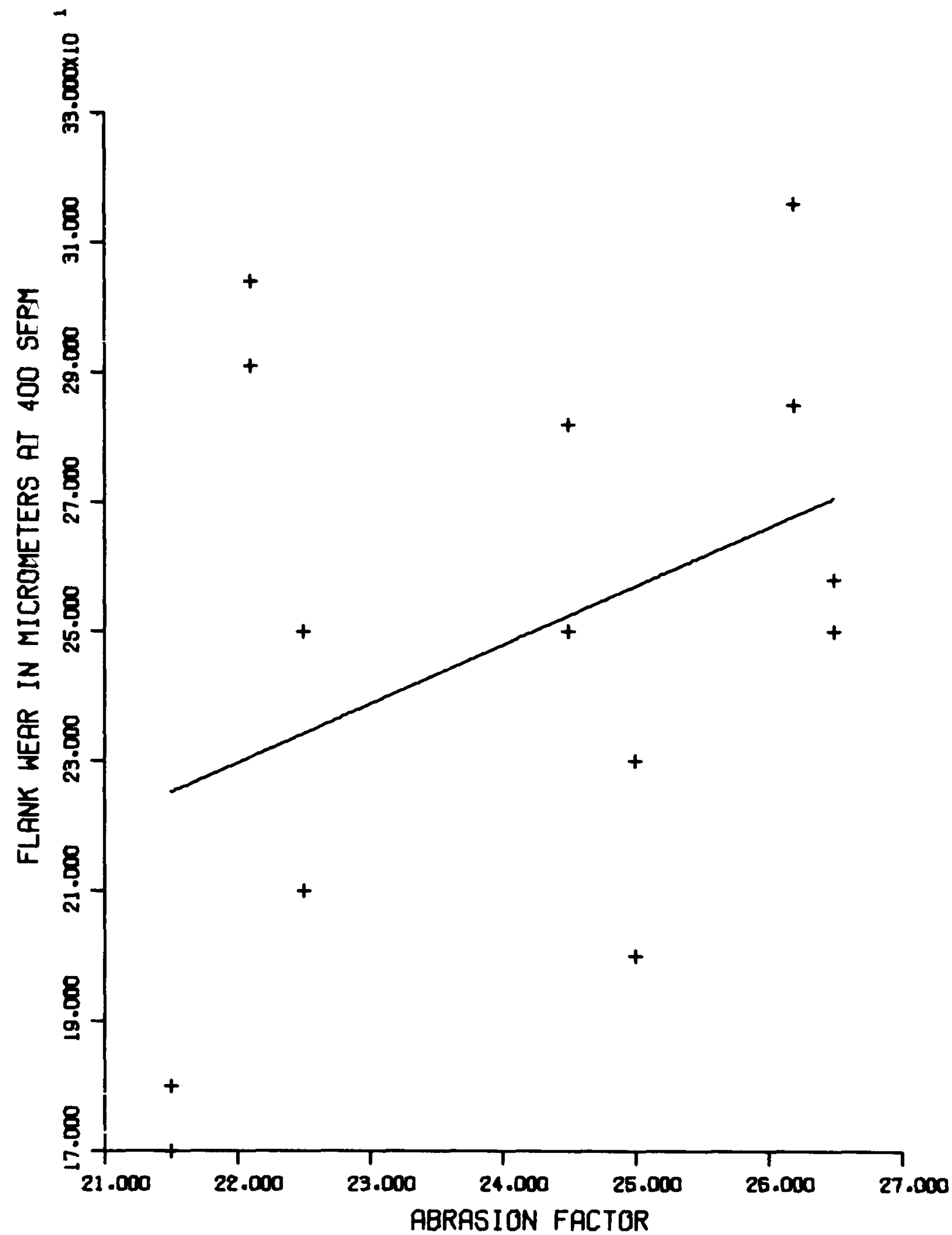
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 36



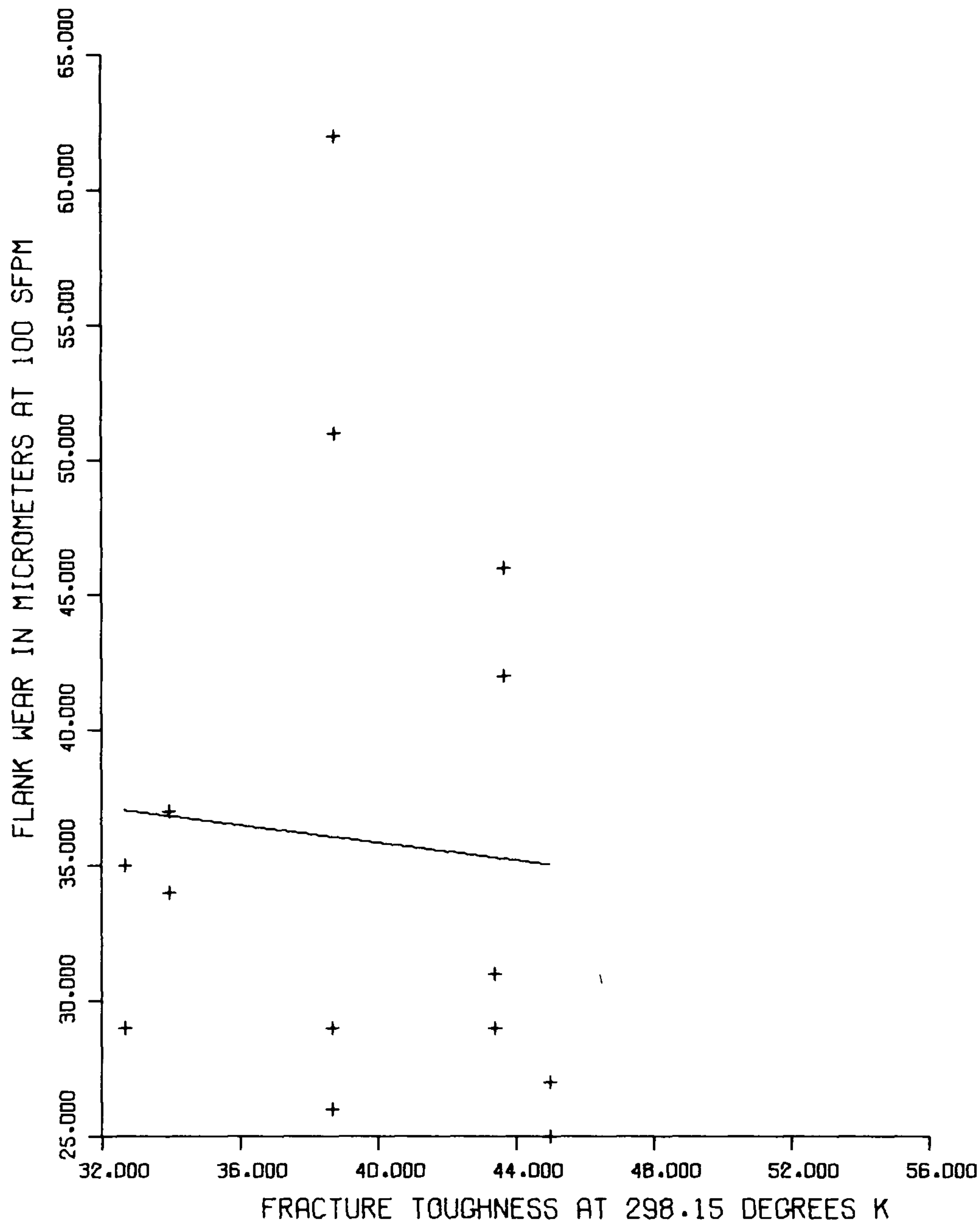
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 37



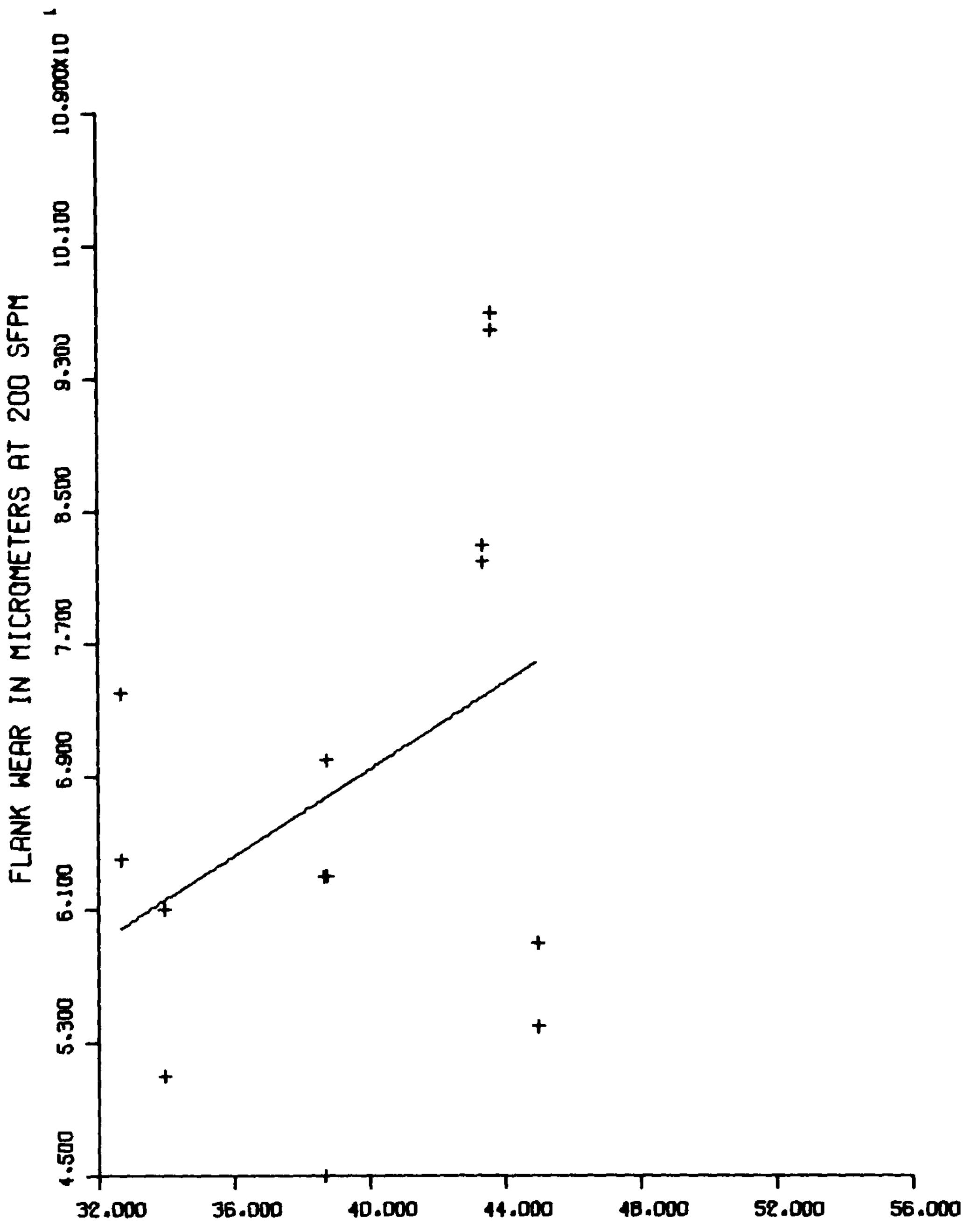
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 38



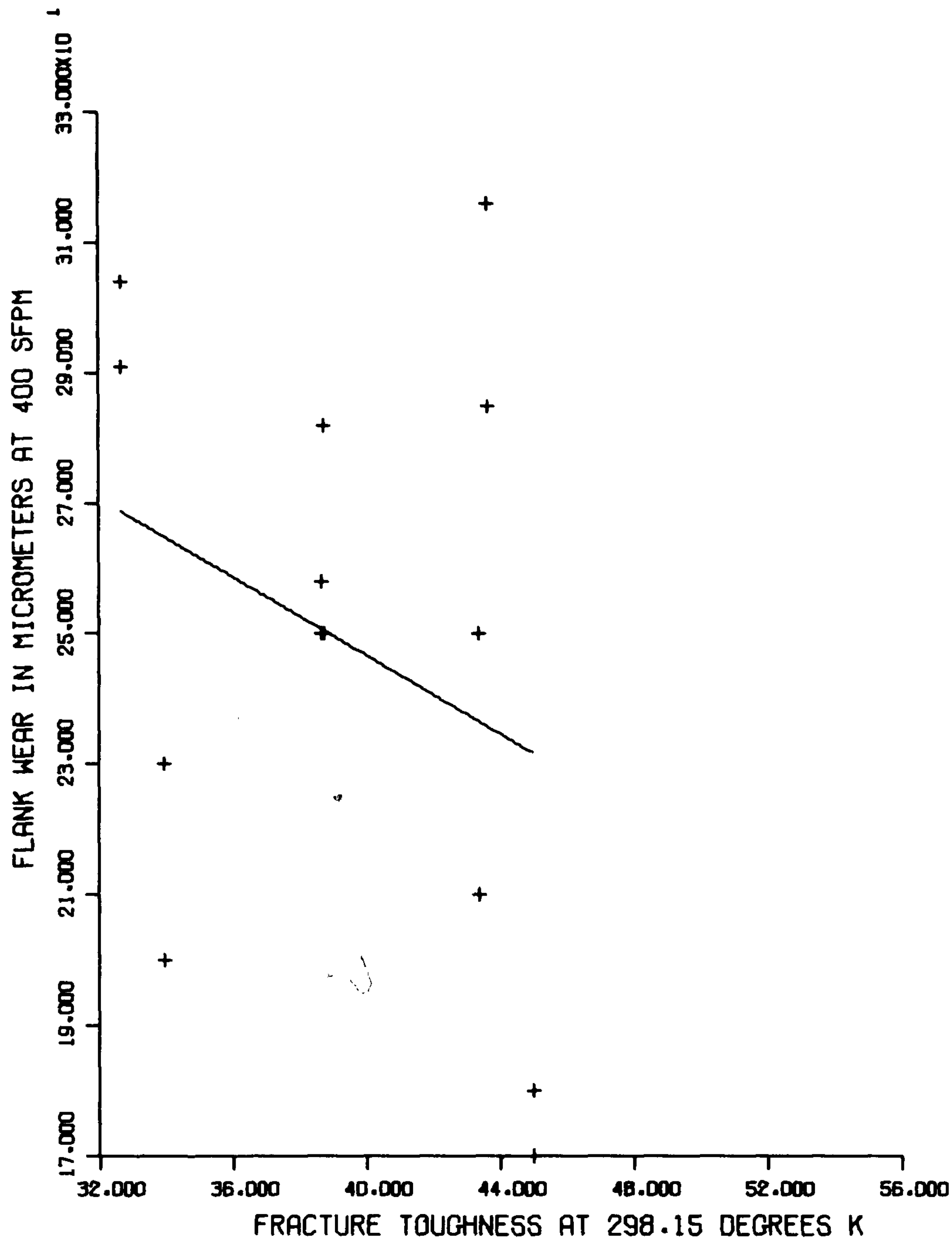
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 39



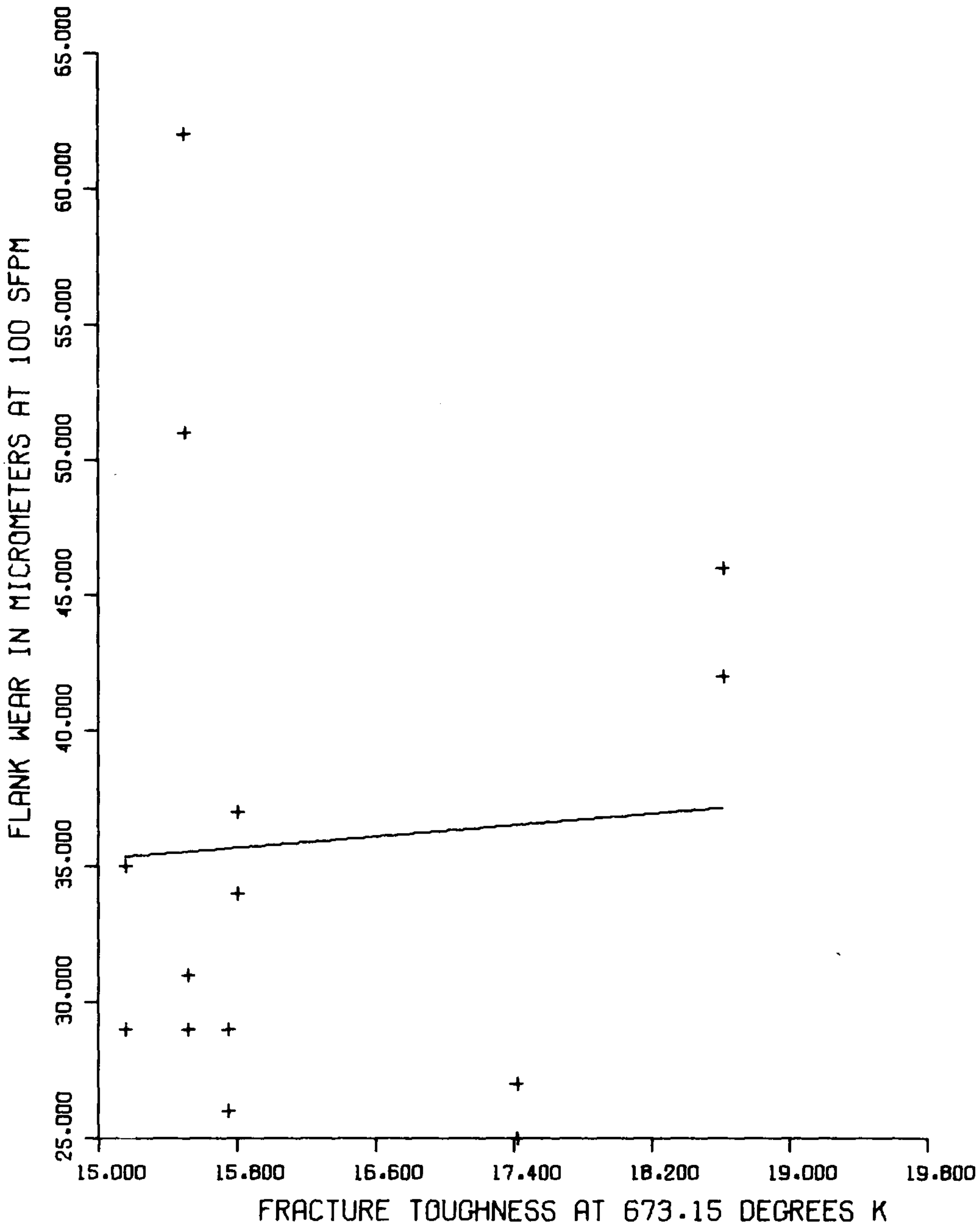
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 40



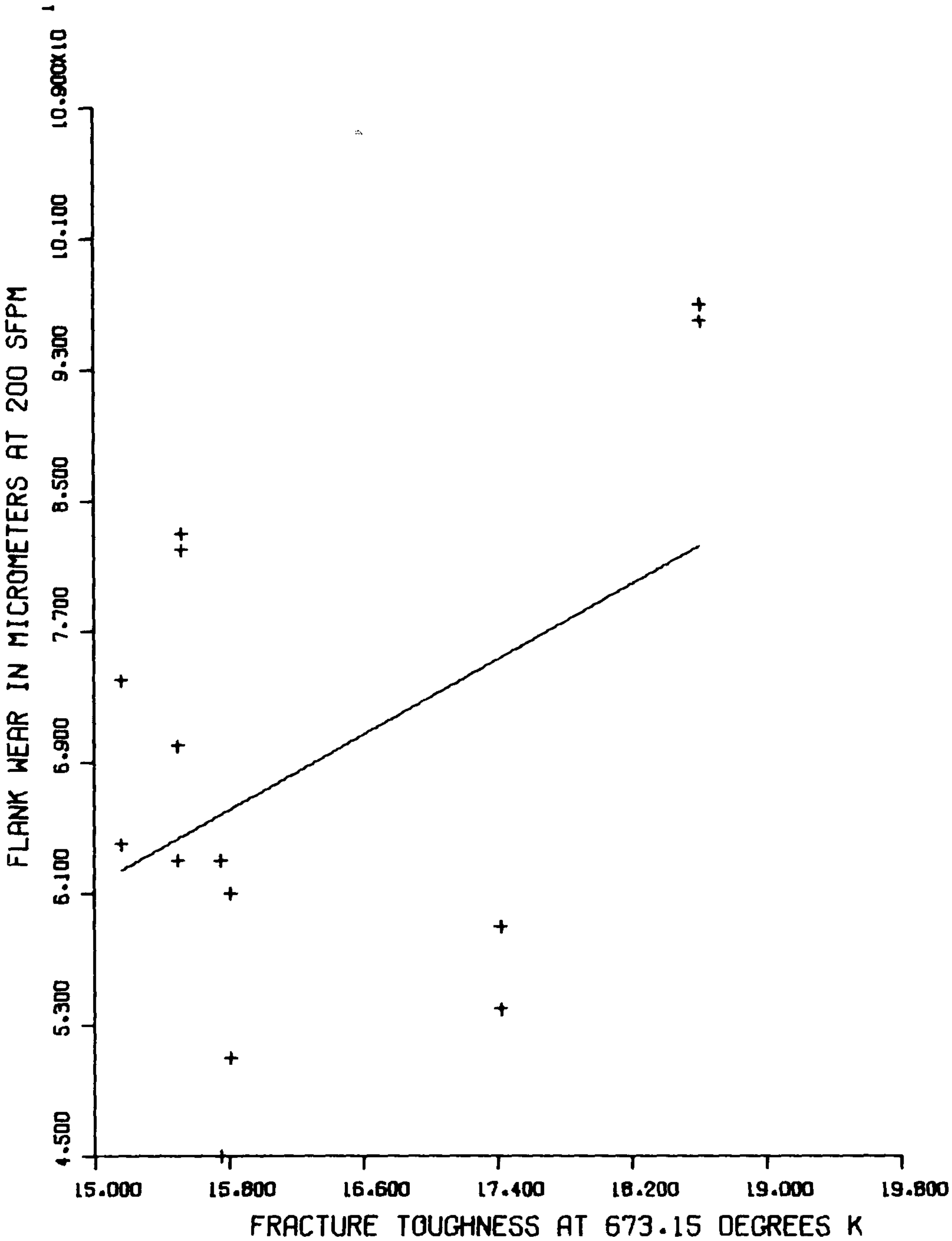
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 41



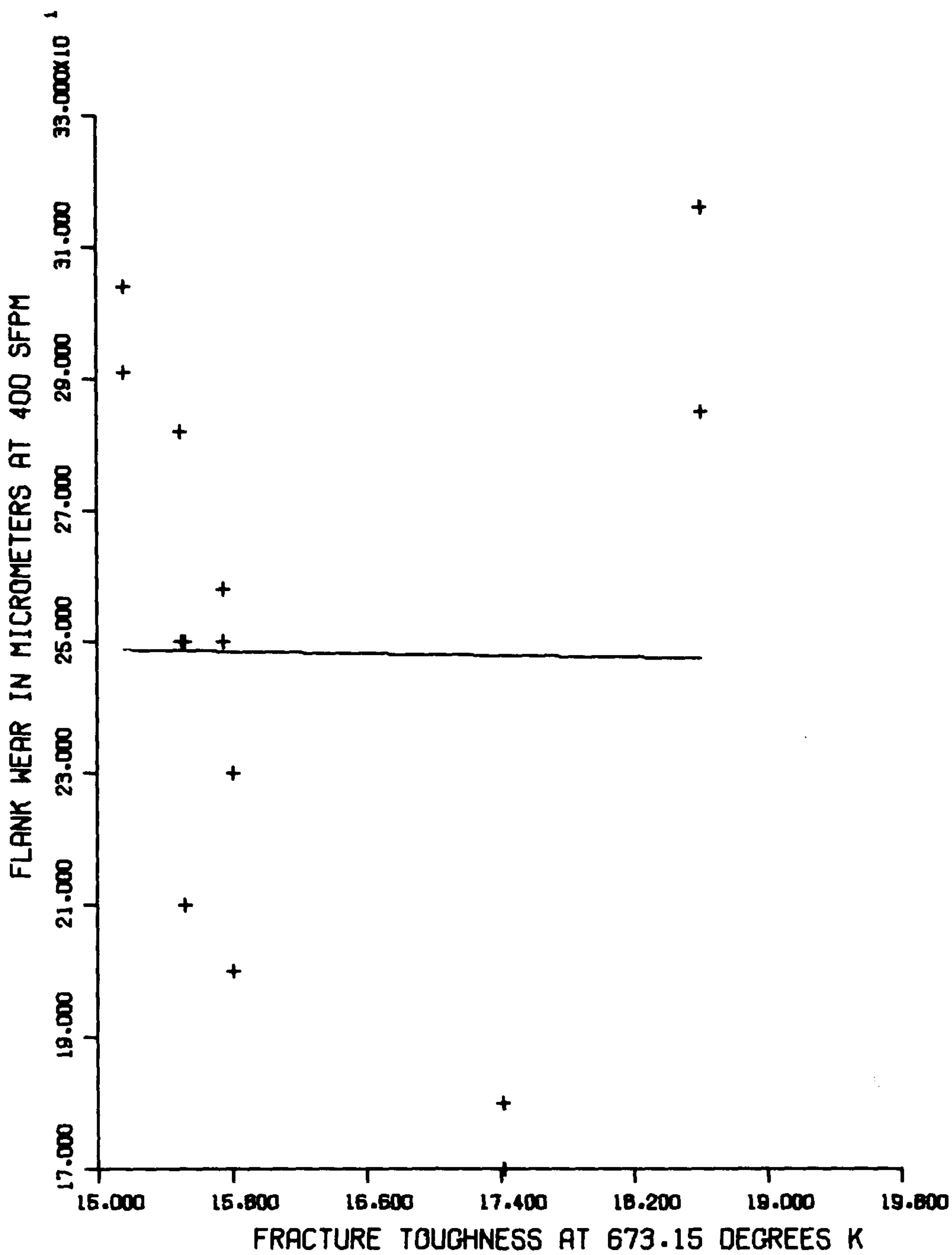
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 42



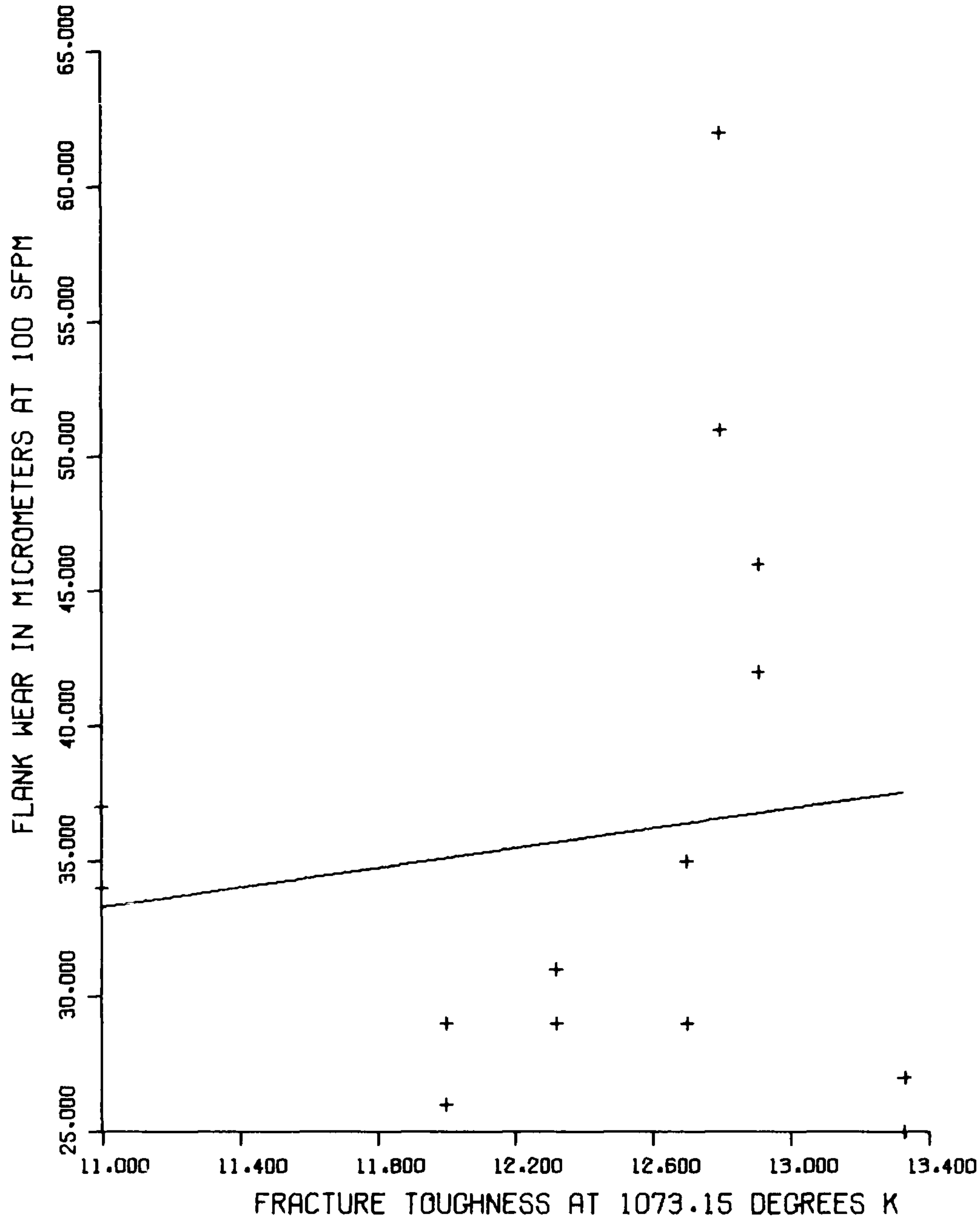
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 43



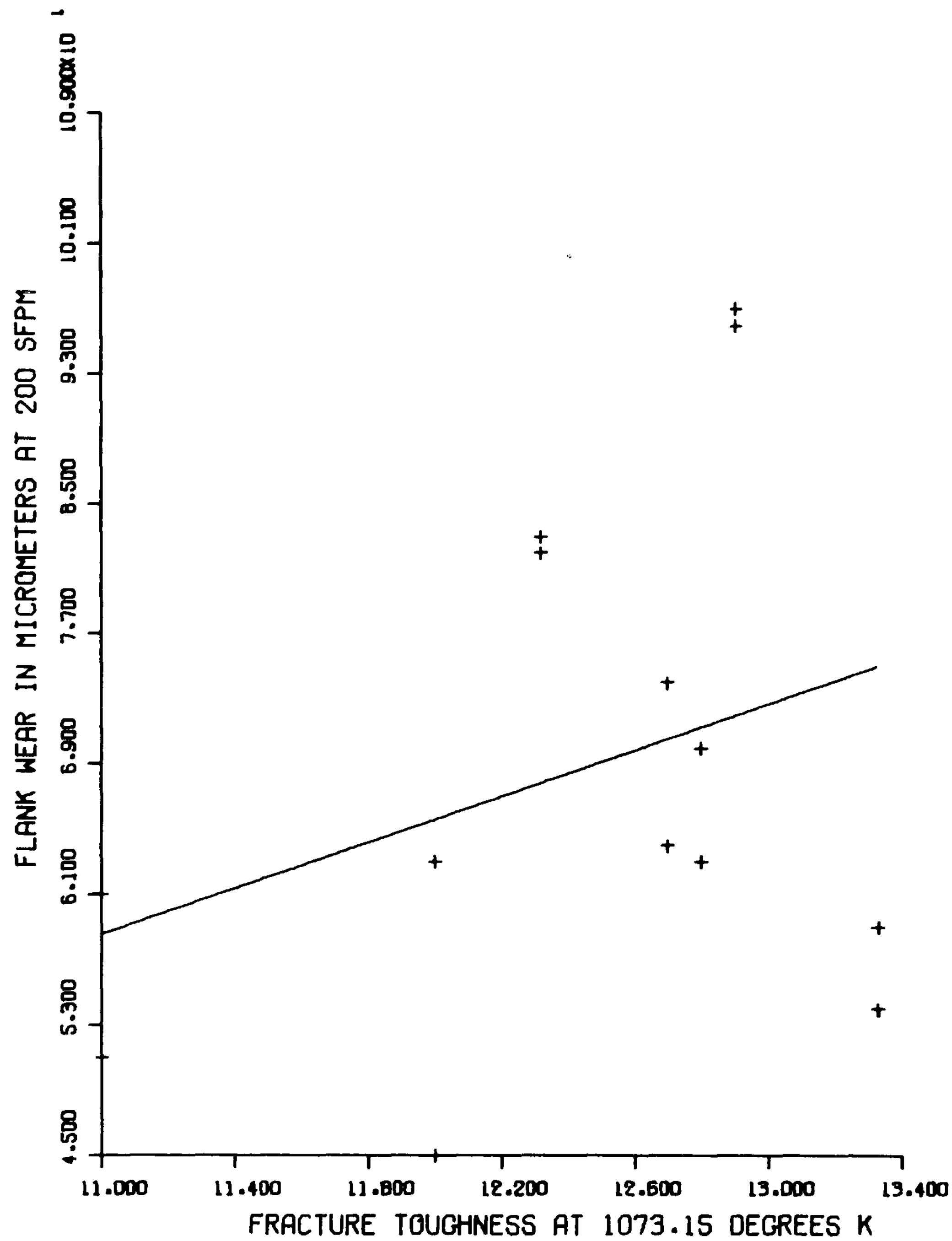
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 44



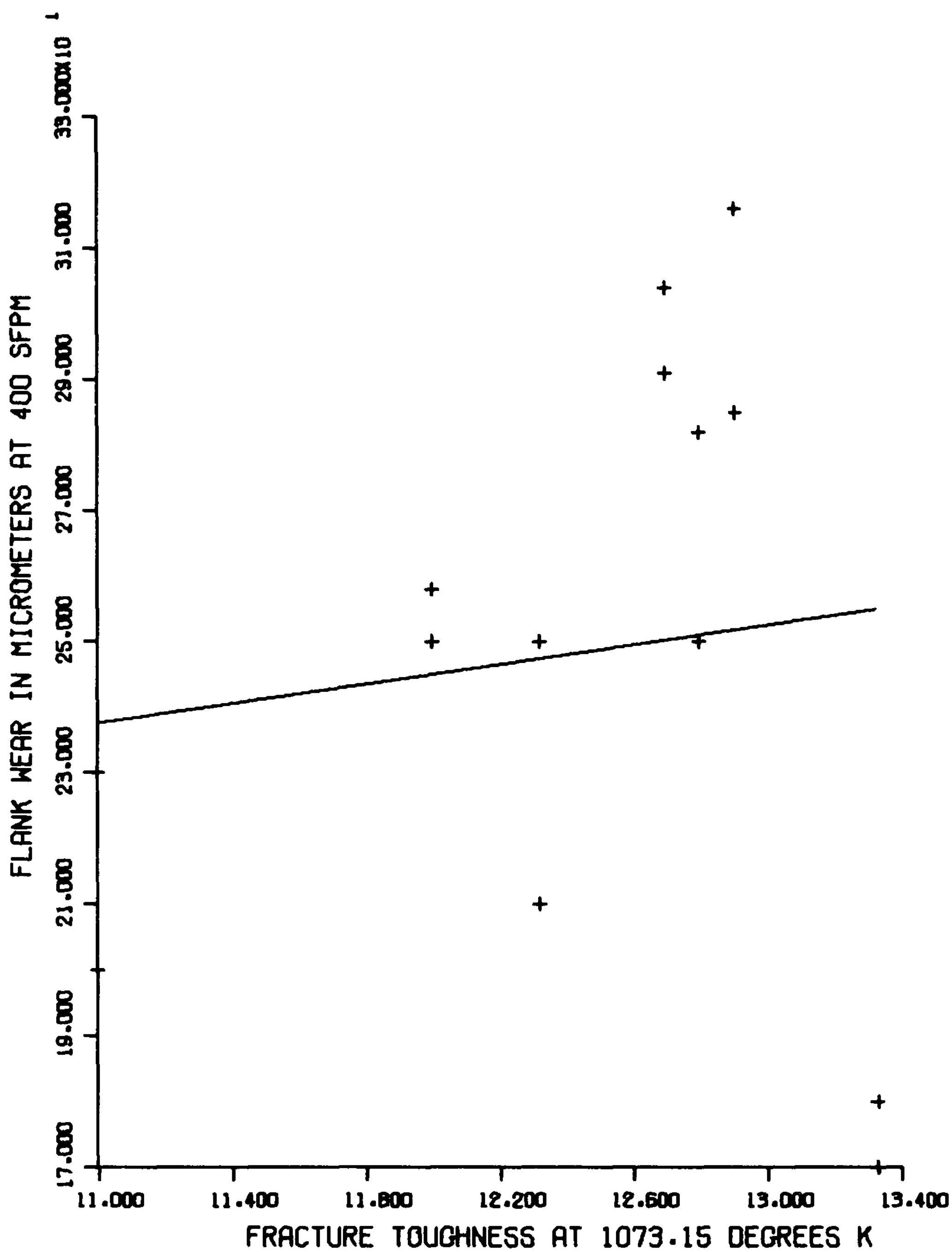
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 45



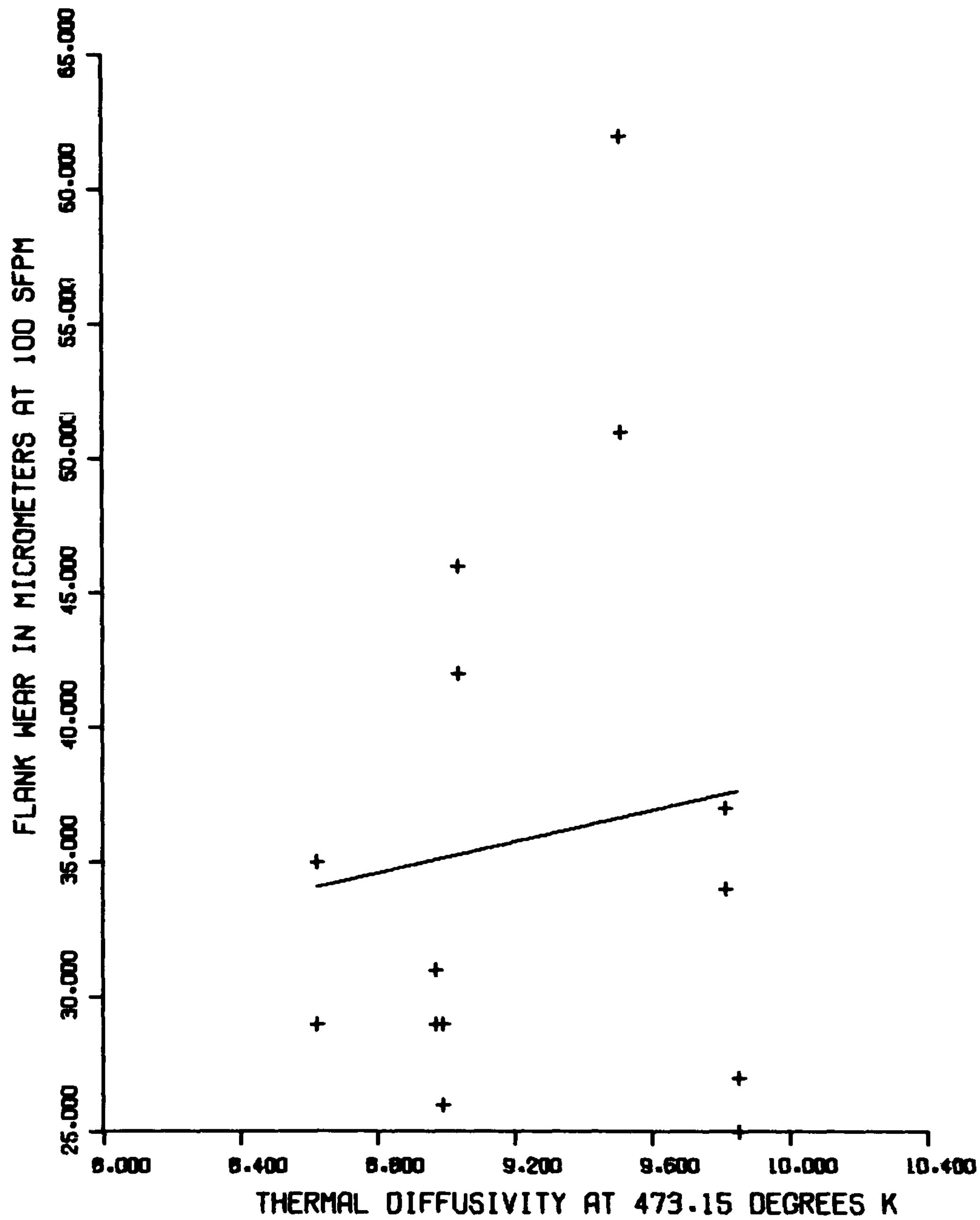
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 46



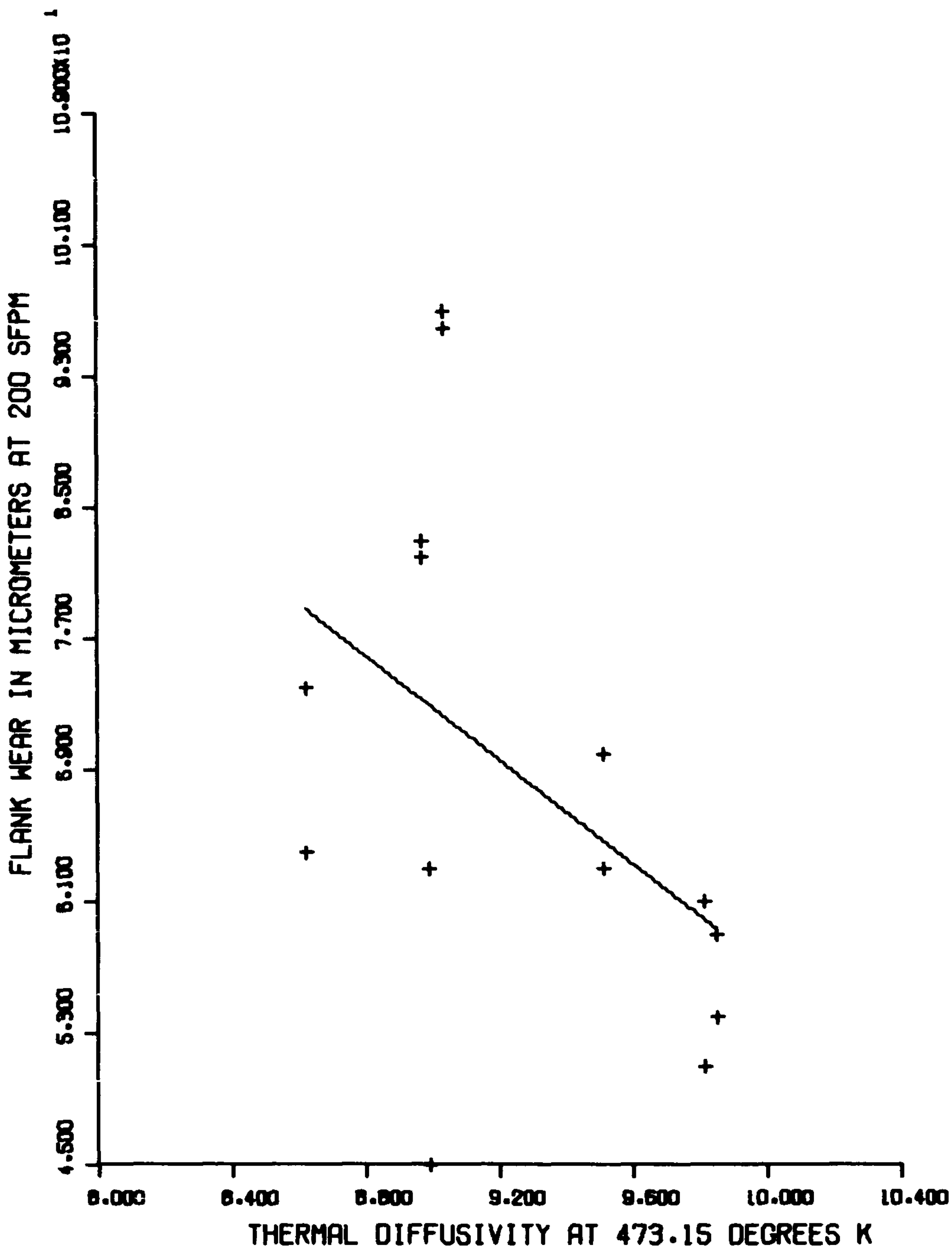
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 47



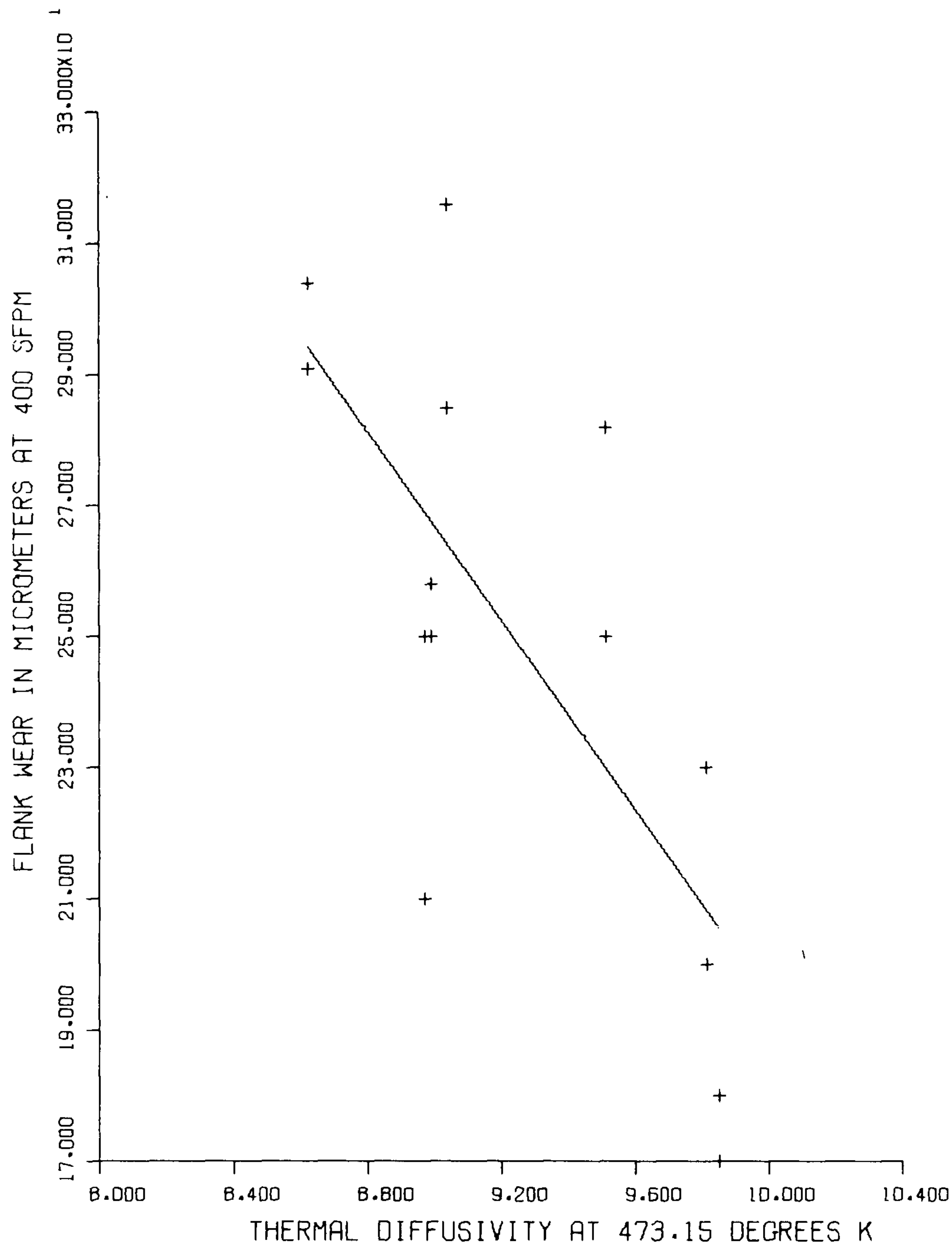
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 48



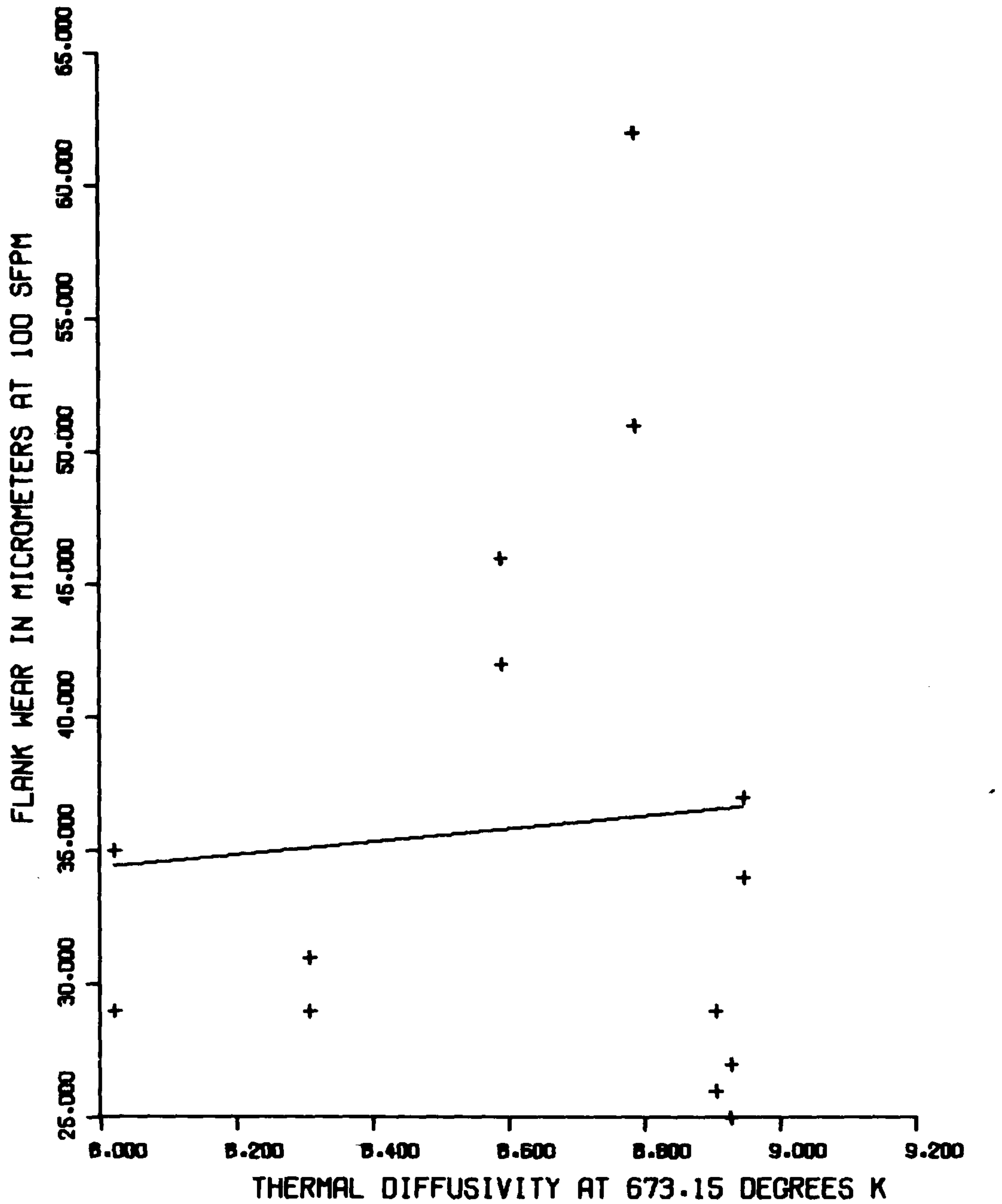
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 49



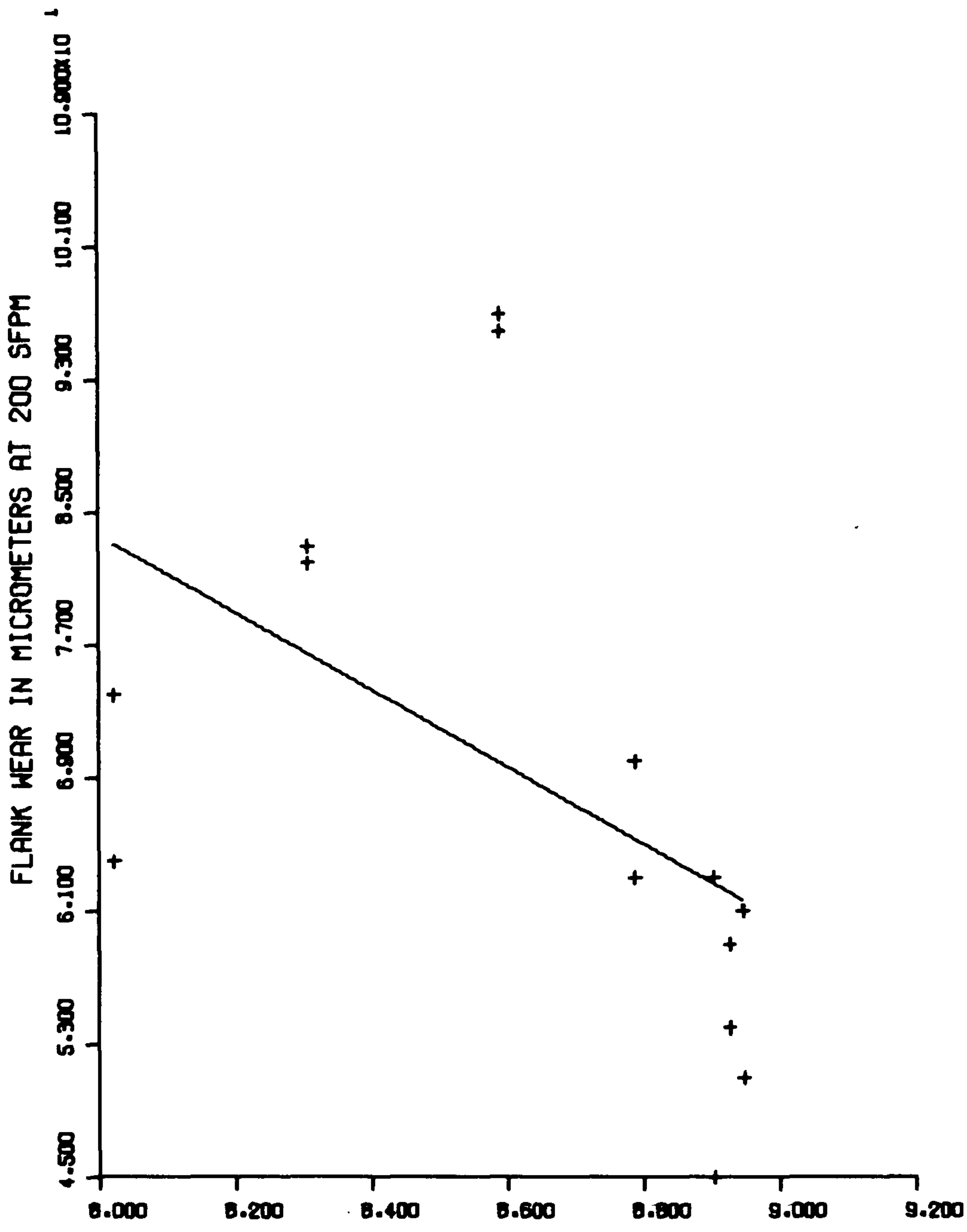
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 50



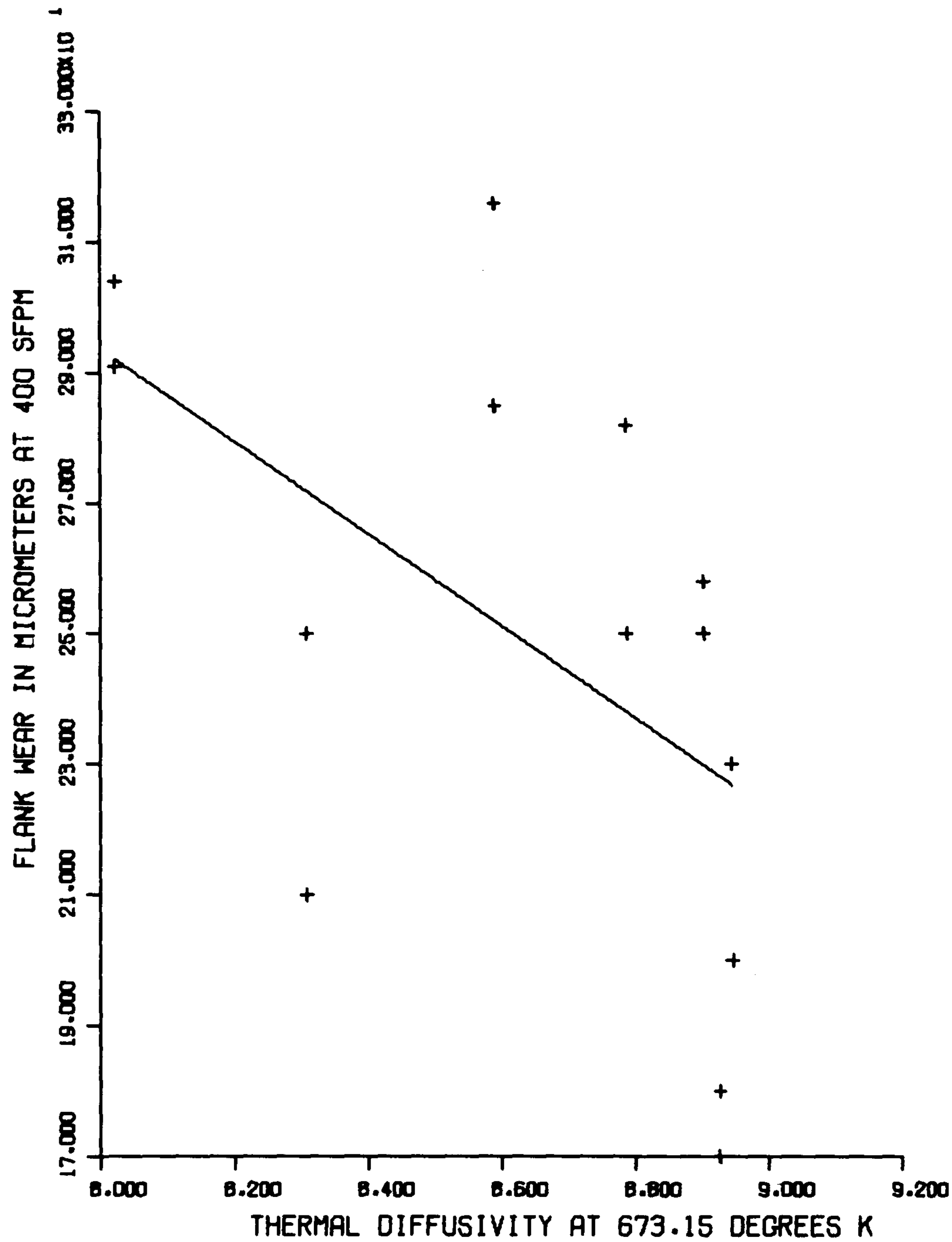
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 51



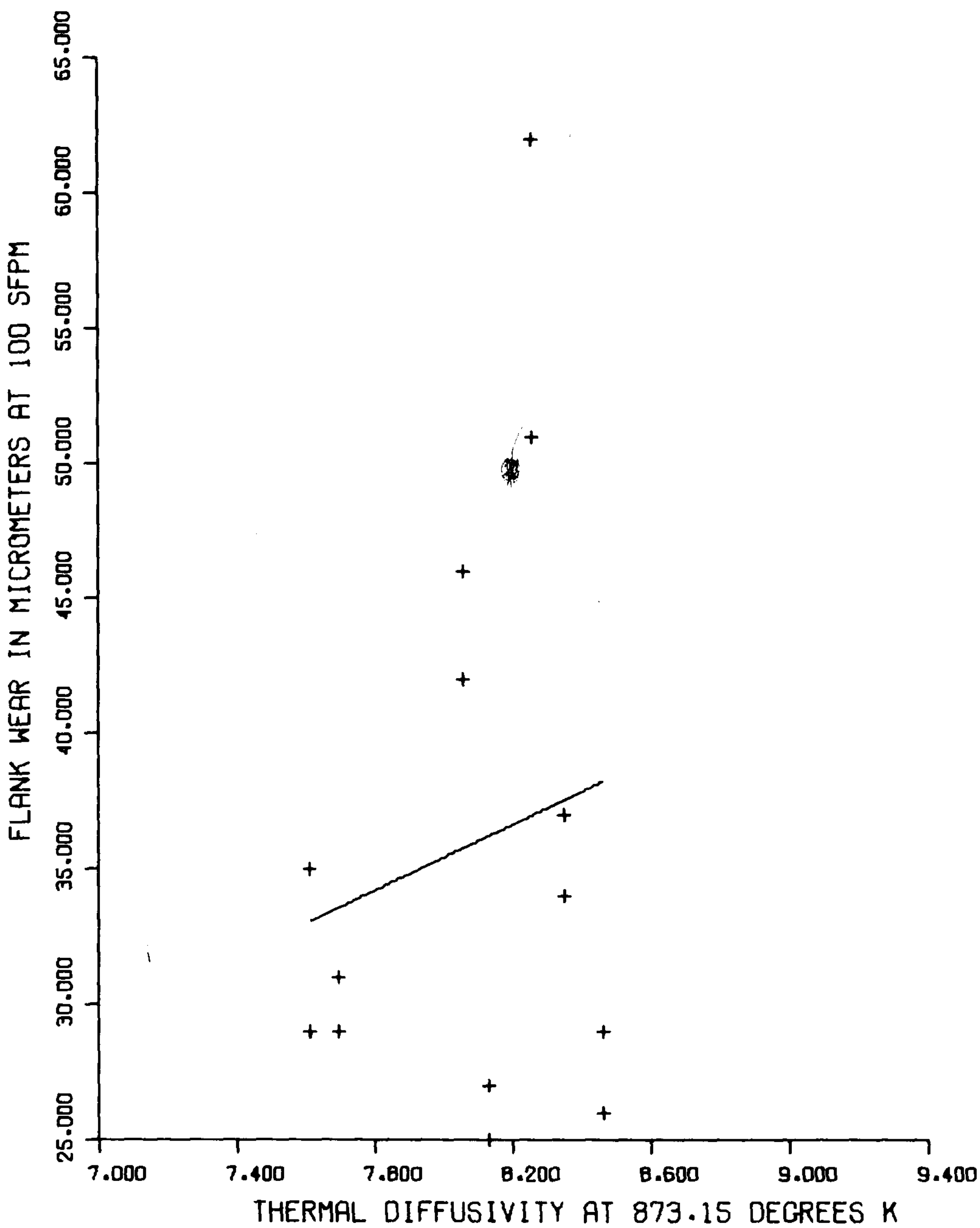
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 52



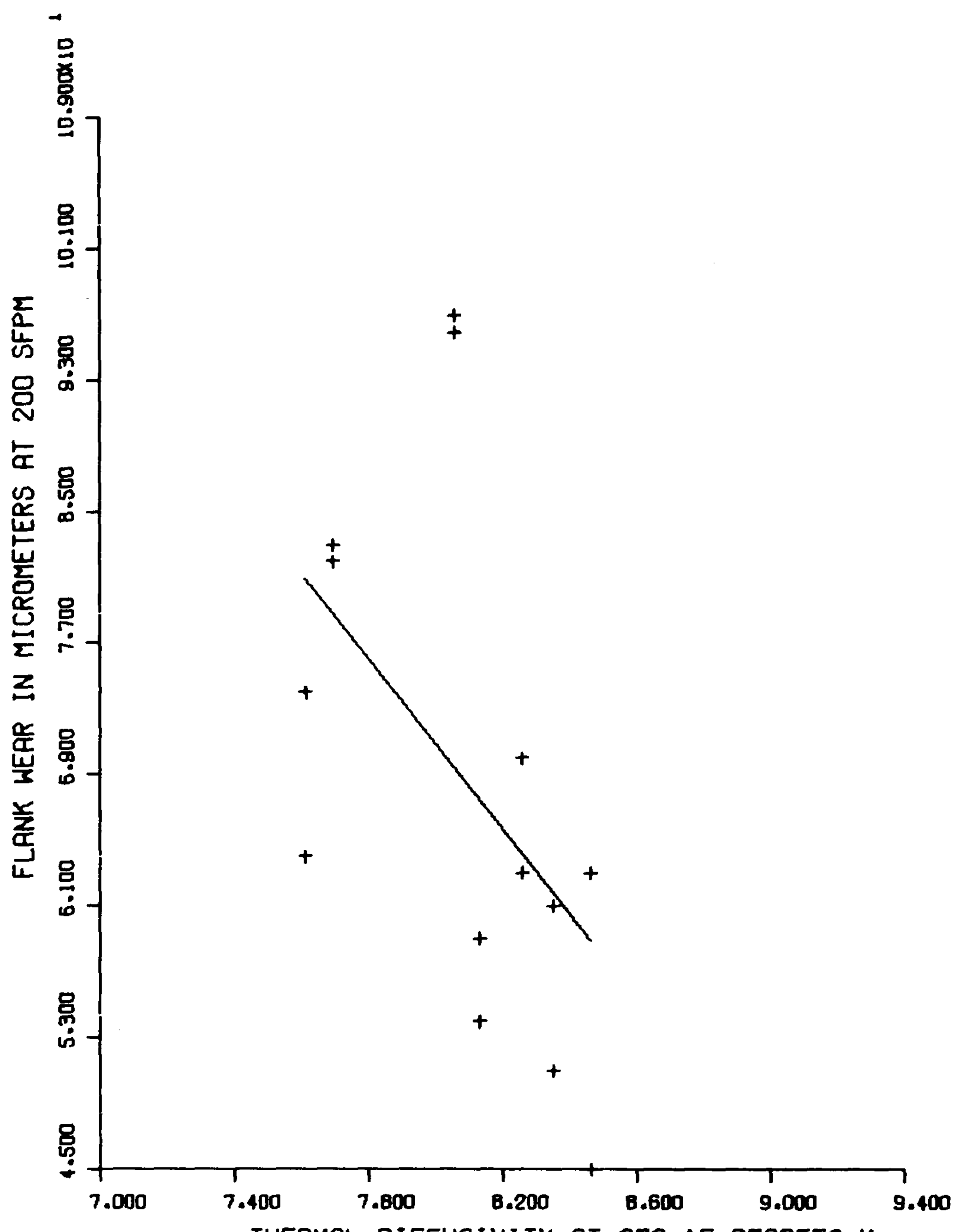
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 53



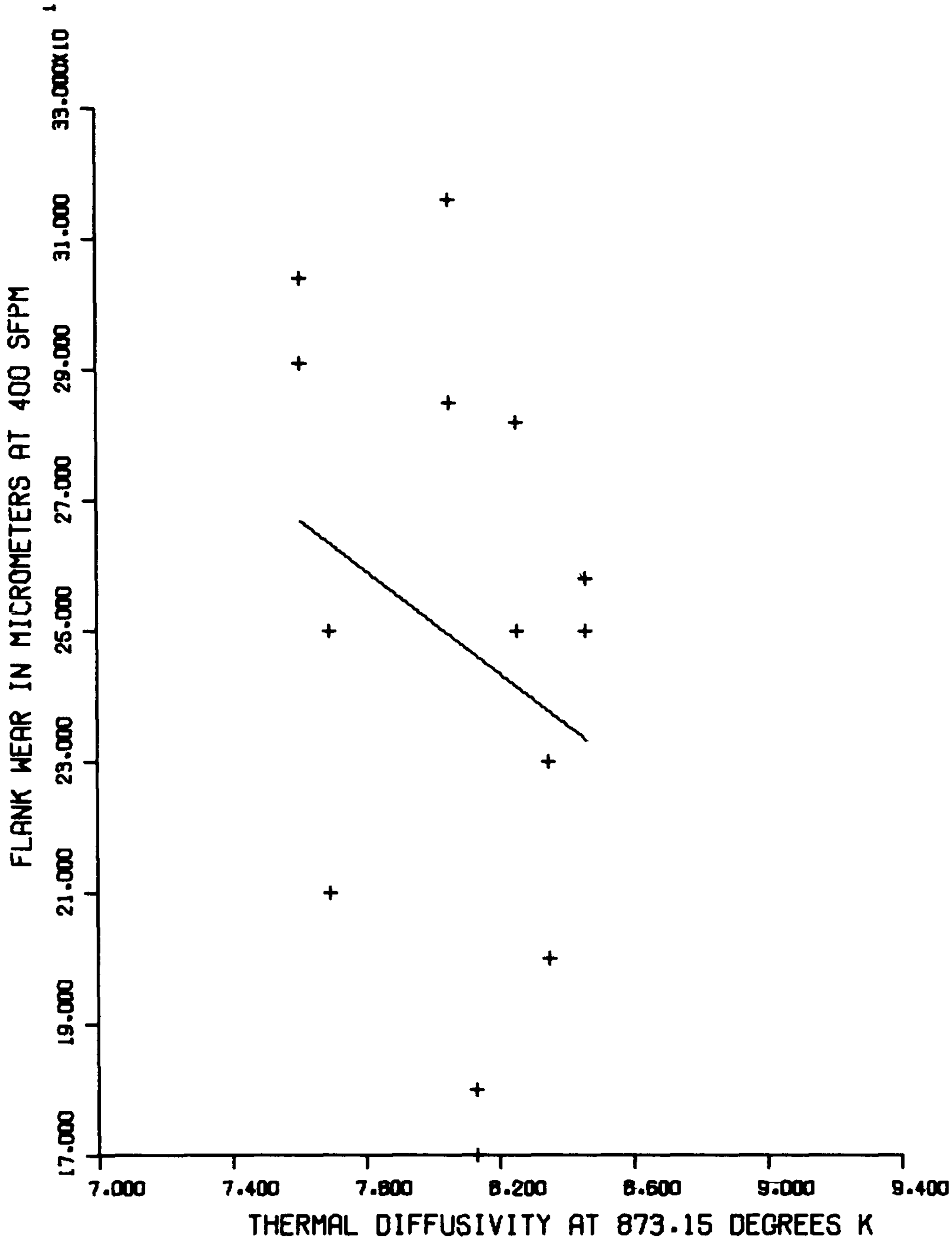
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 54



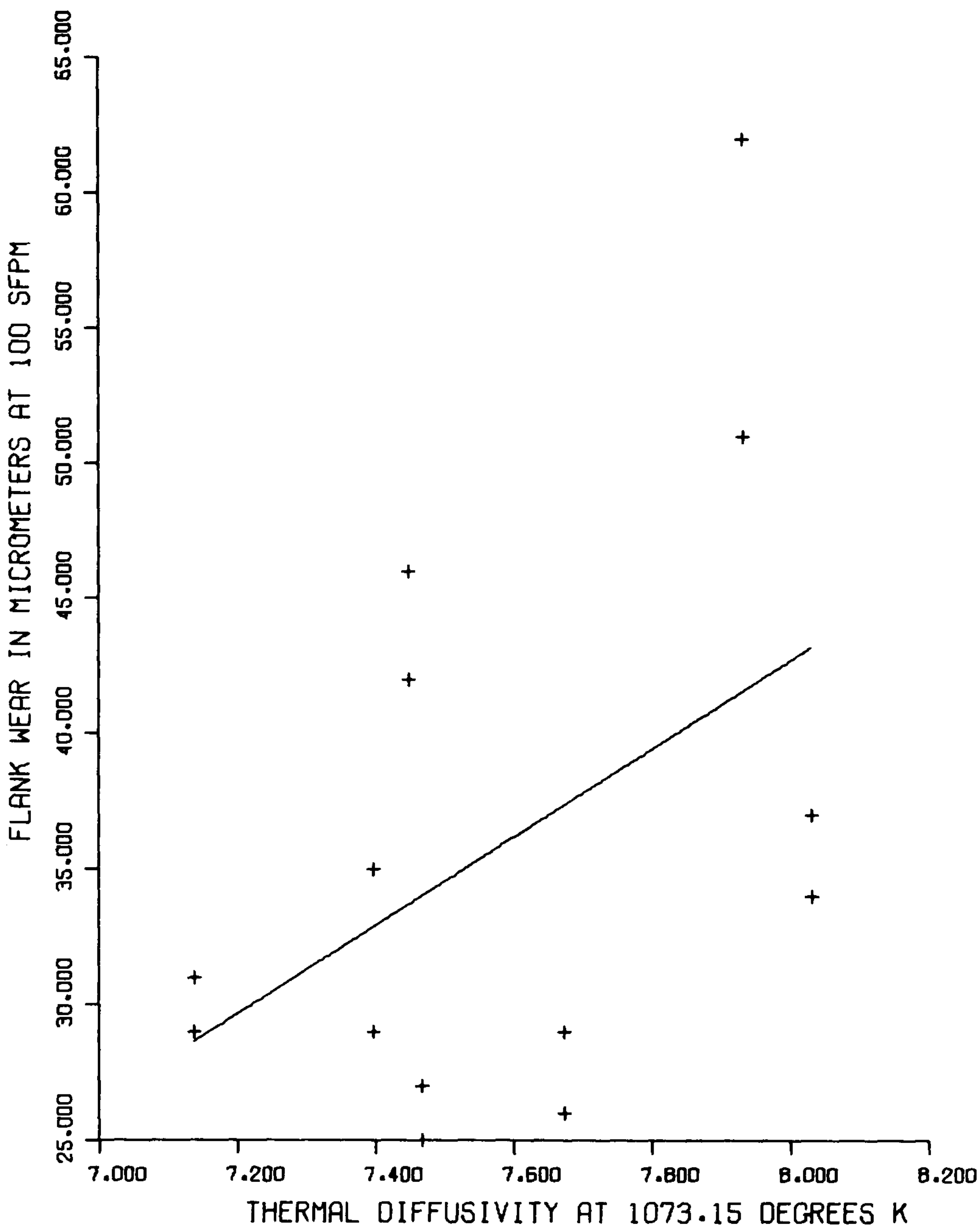
FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 55



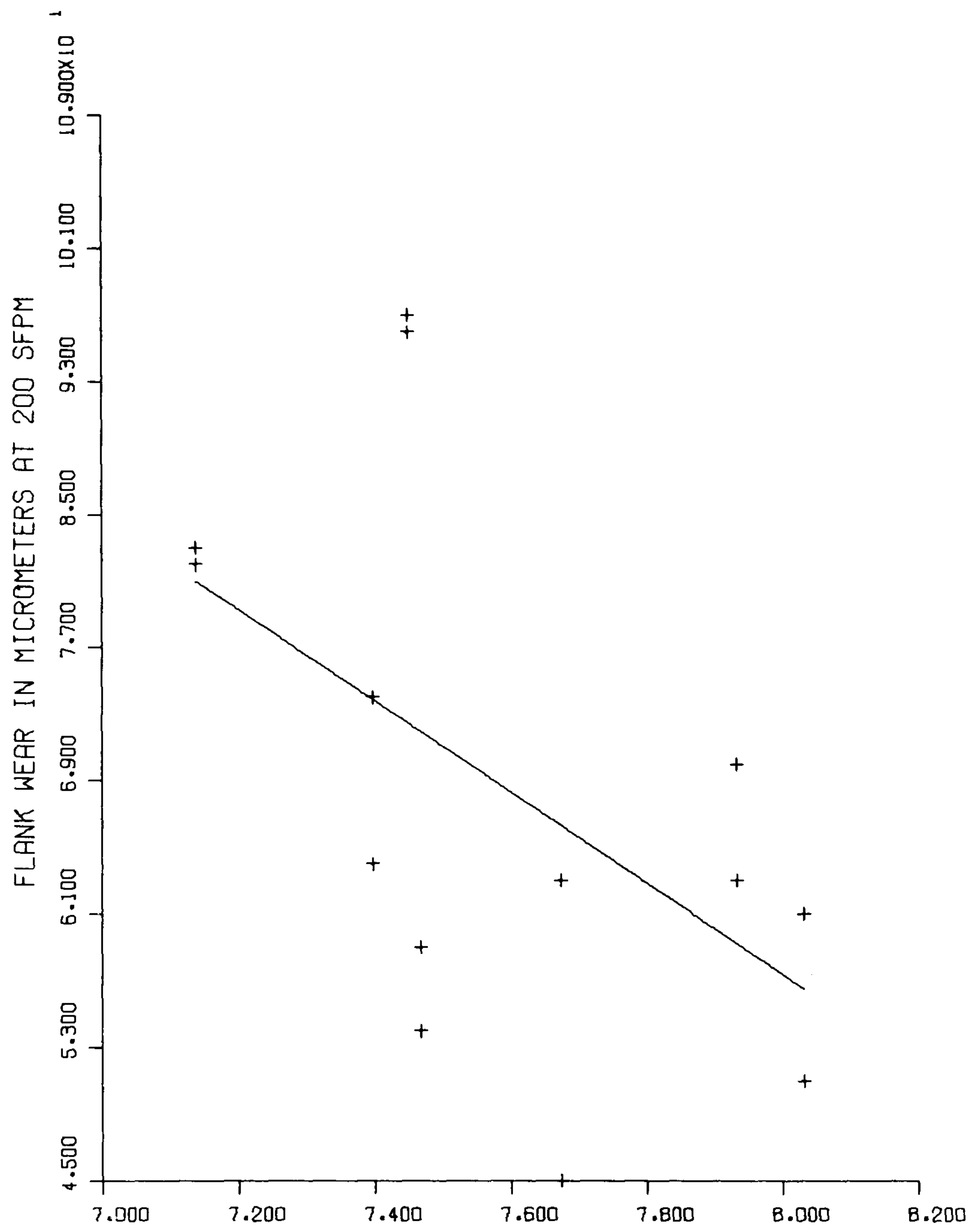
FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 56



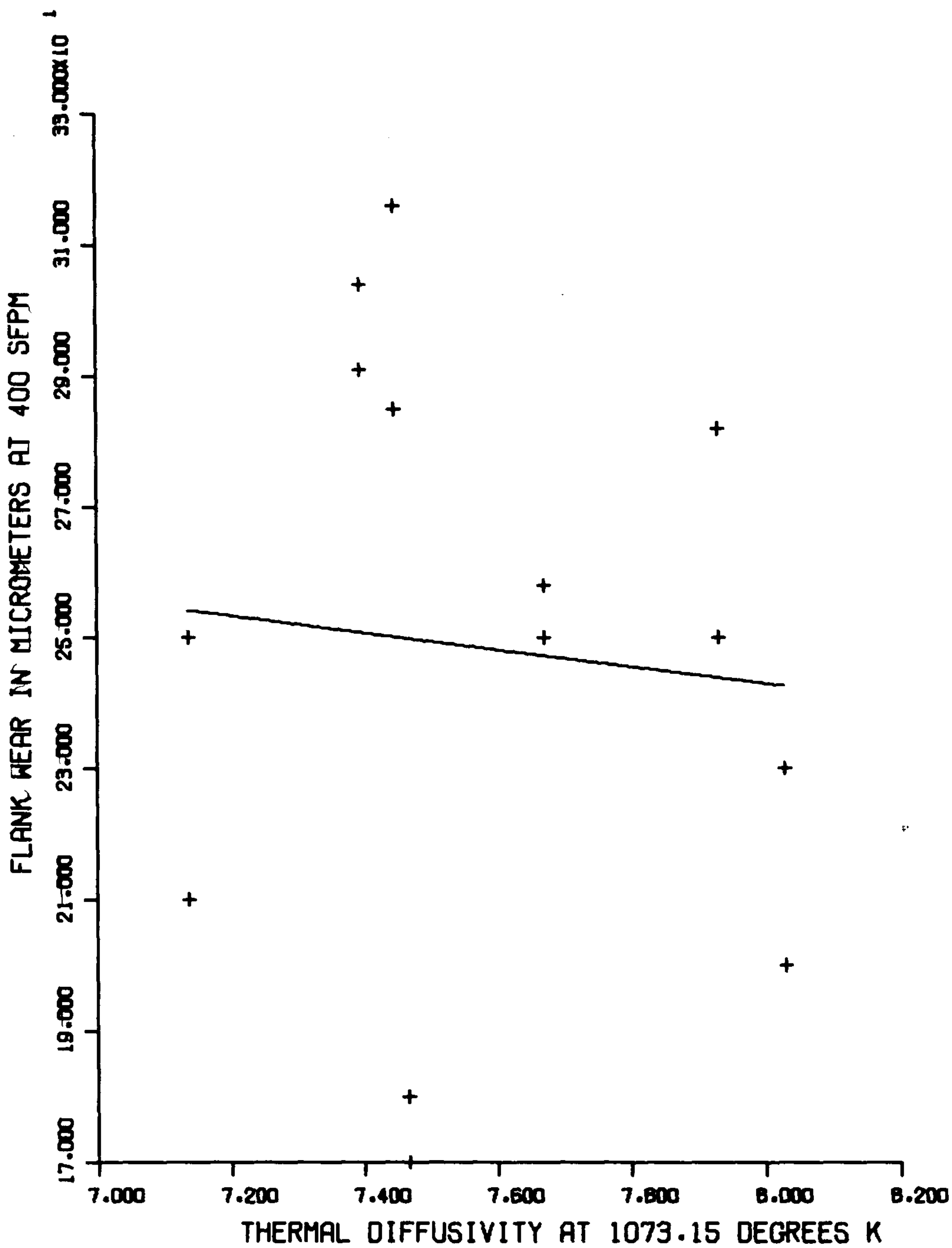
FLANK WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 57



FLANK WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 58



FLANK WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 59

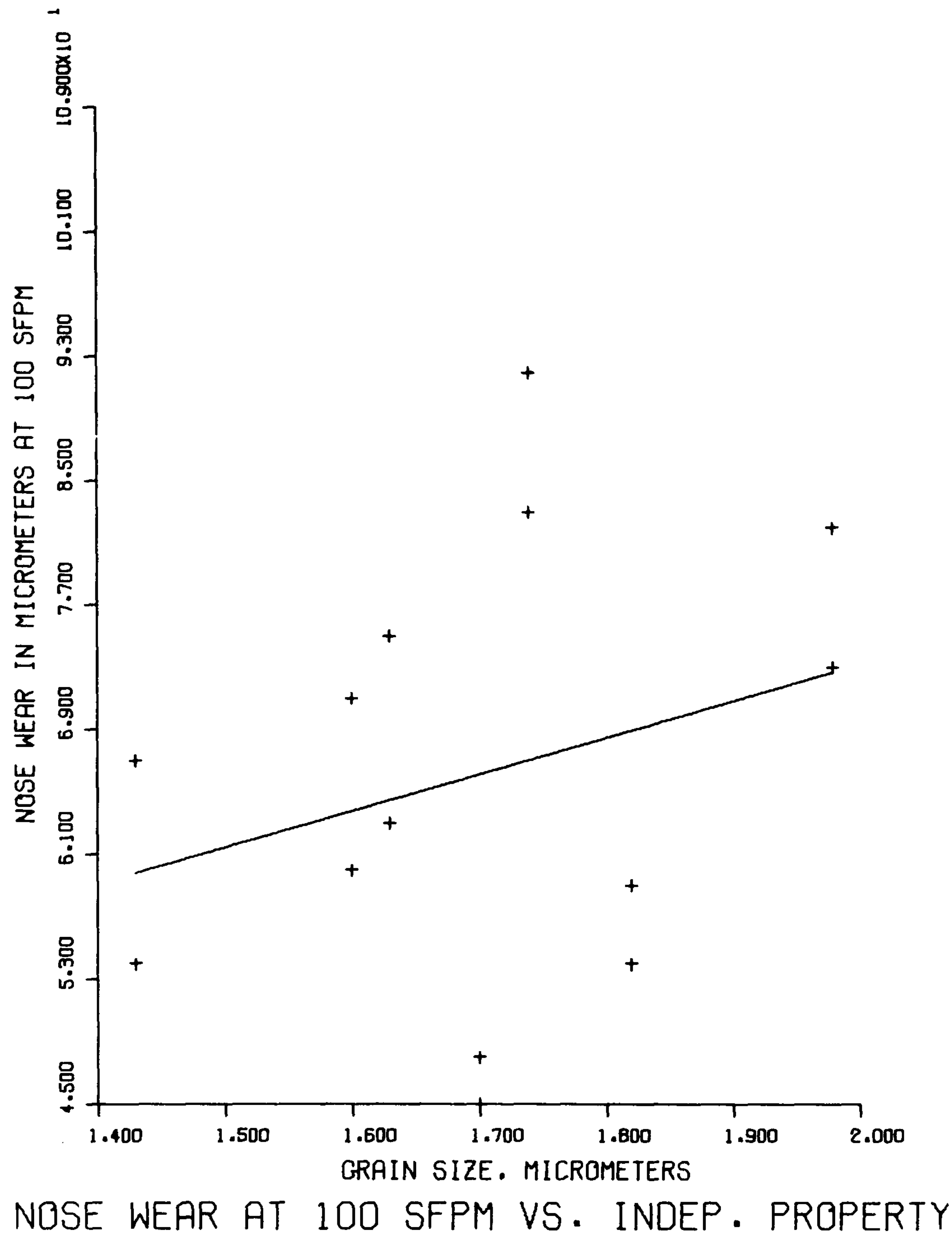
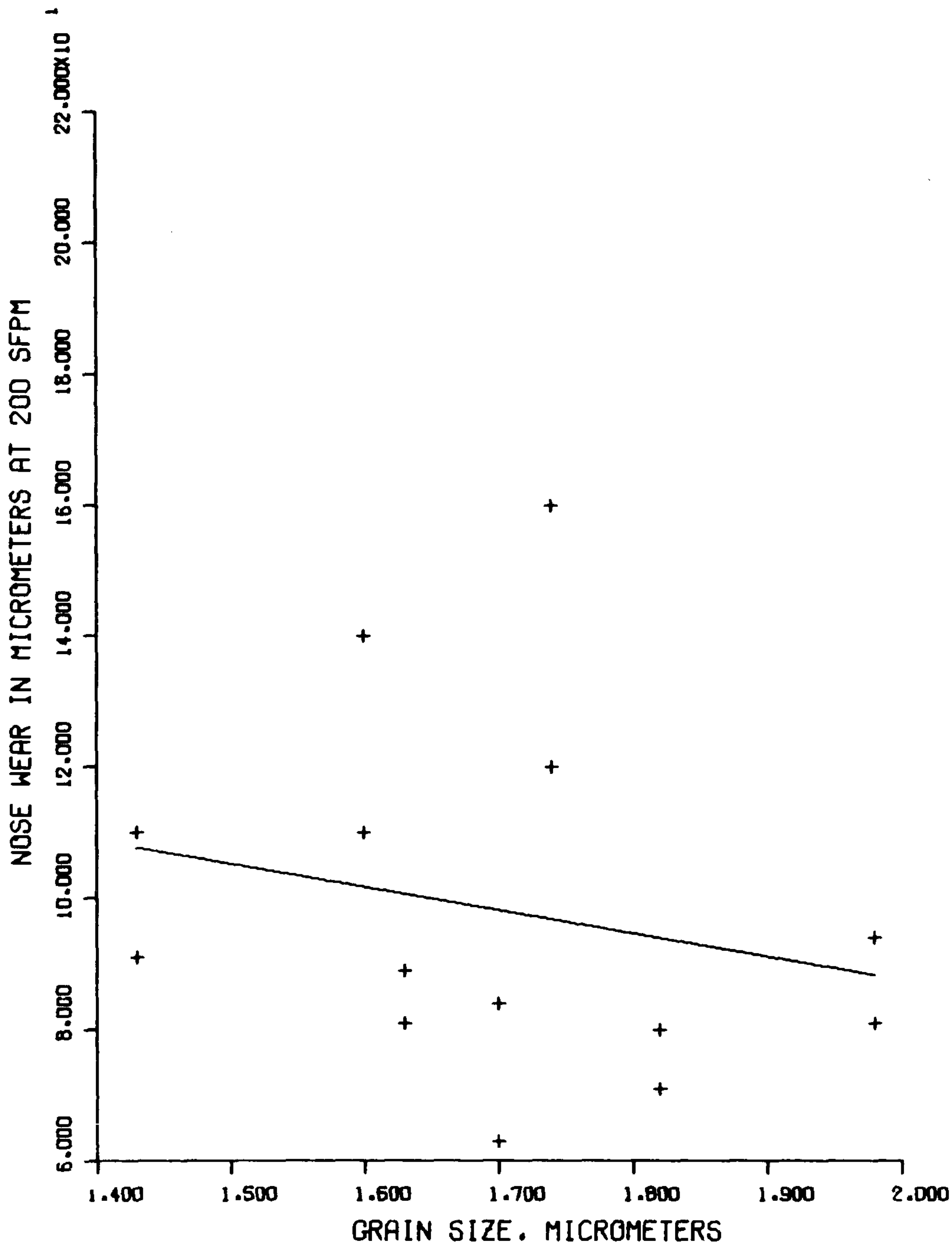
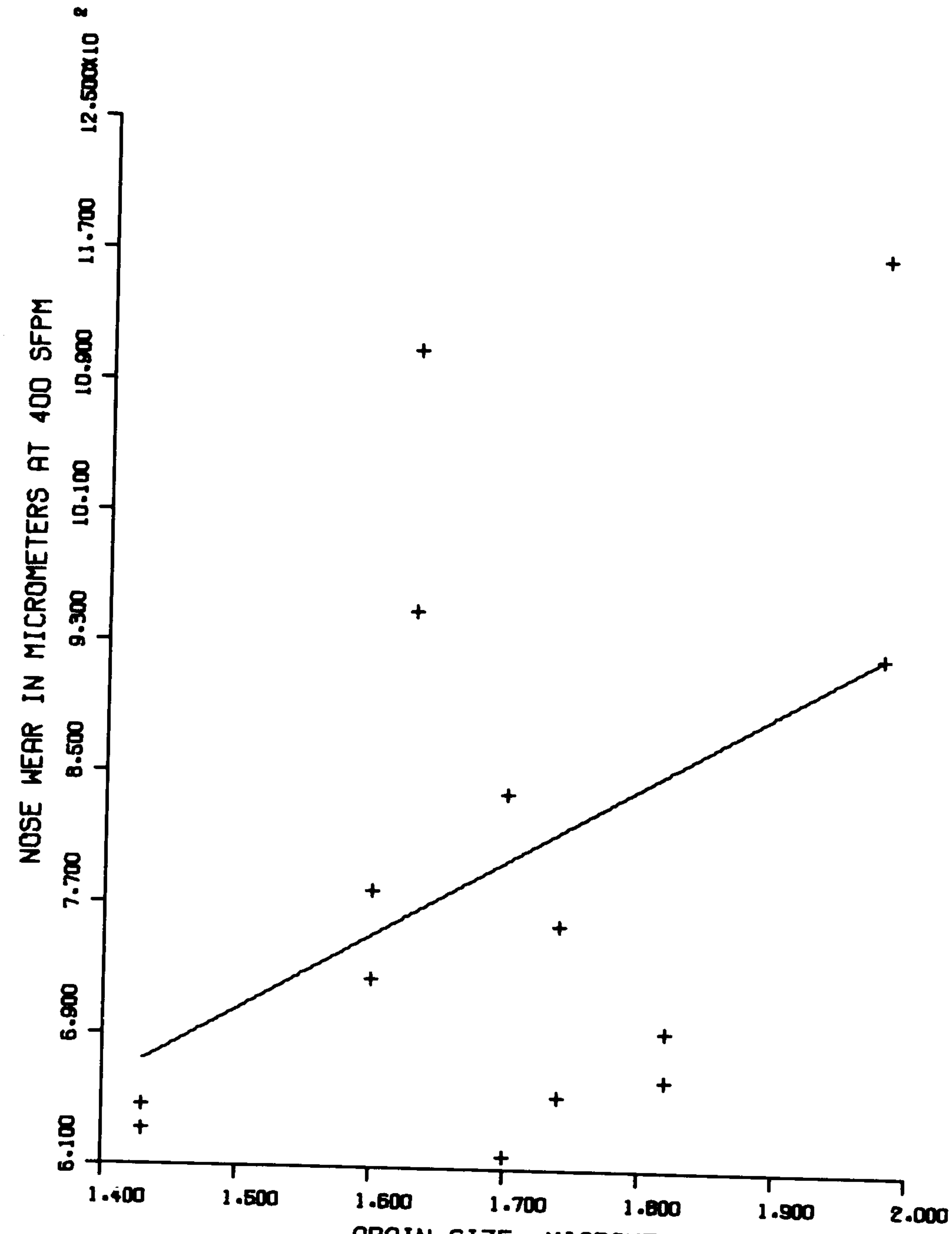

10.900X10 1
10.100
9.300
8.500
7.700
6.900
6.100
5.300
4.500
NOSE WEAR IN MICROMETERS AT 100 SFPM
1.400
1.500
1.600
1.700
1.800
1.900
2.000
GRAIN SIZE, MICROMETERS
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 60



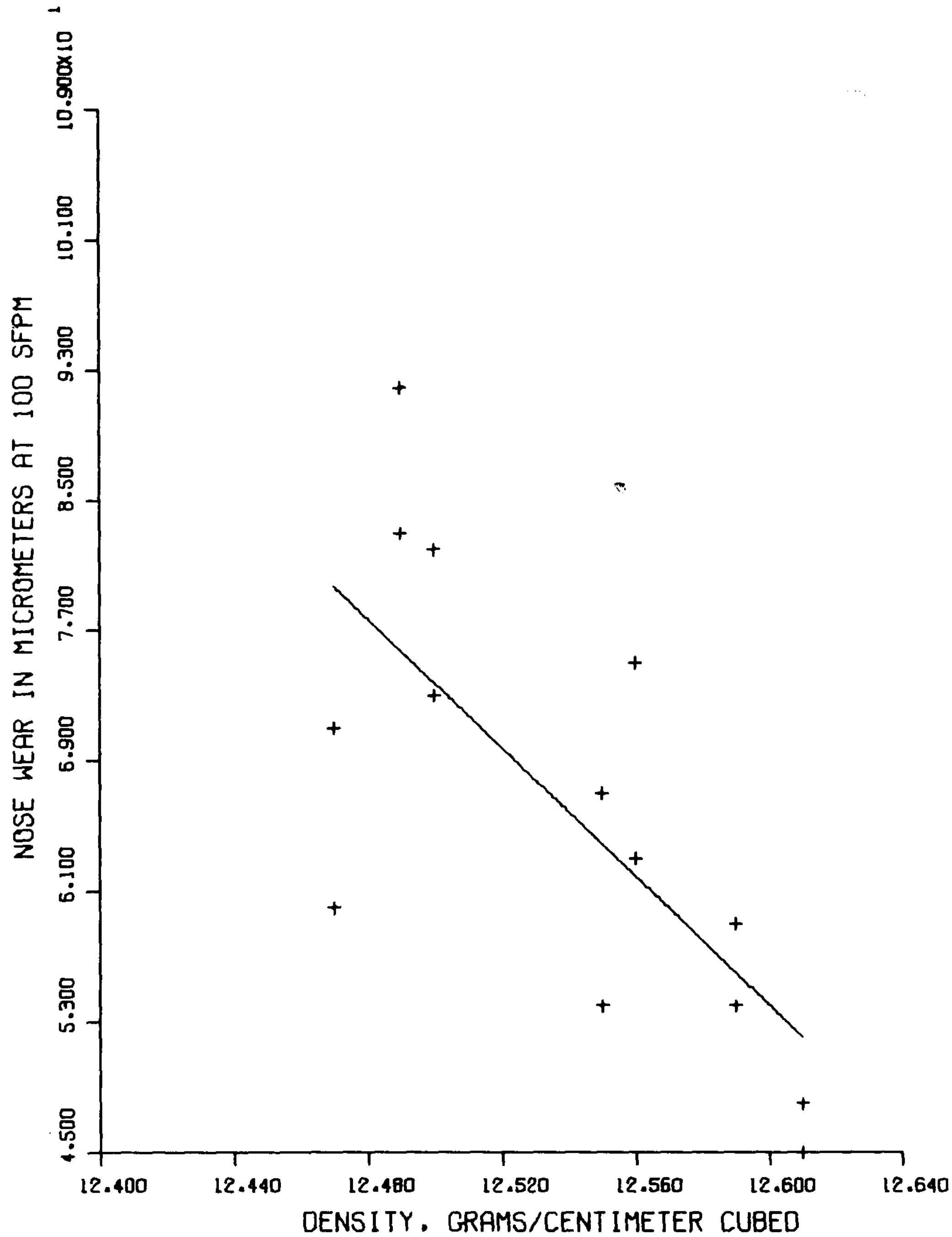
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 61



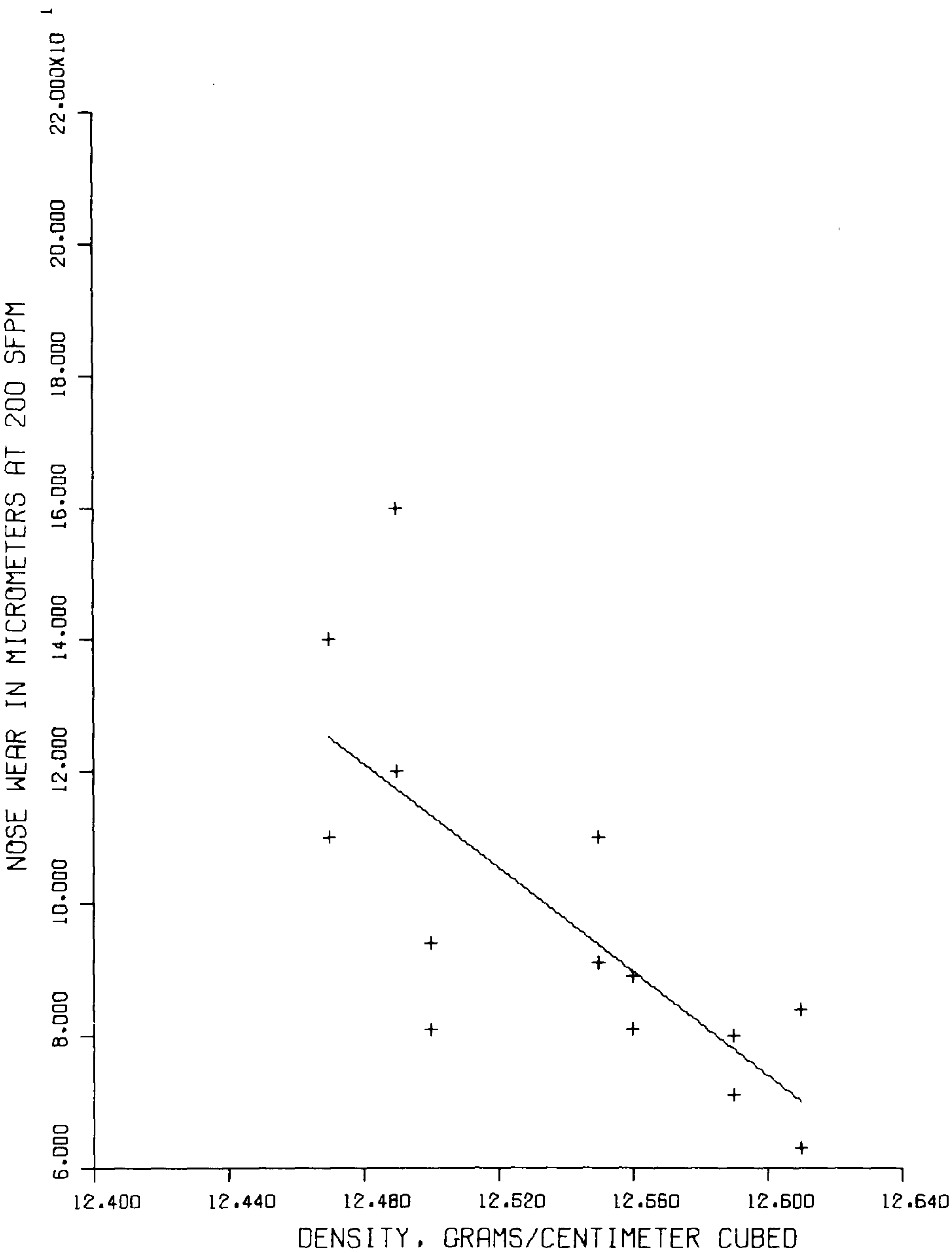
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 62



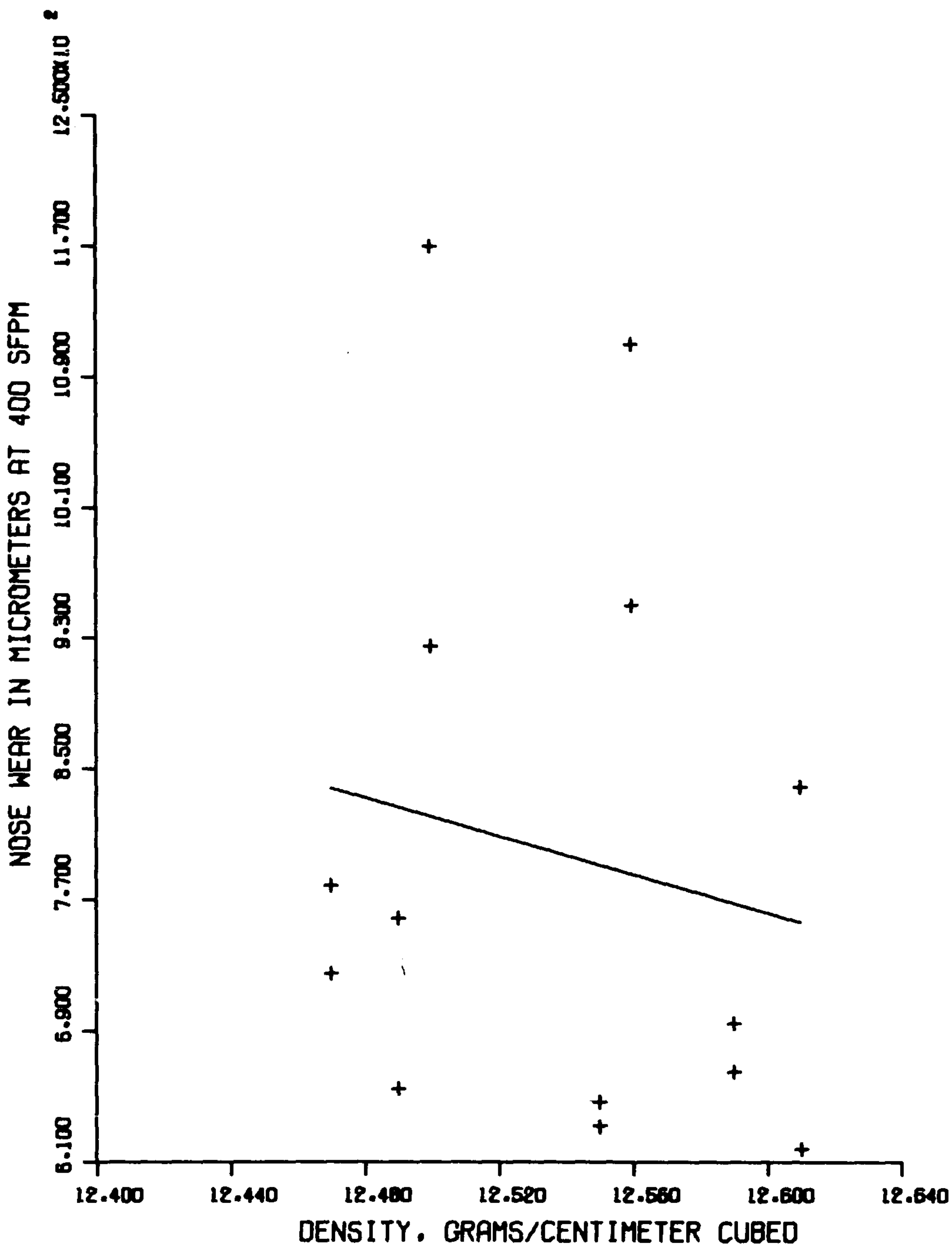
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 63



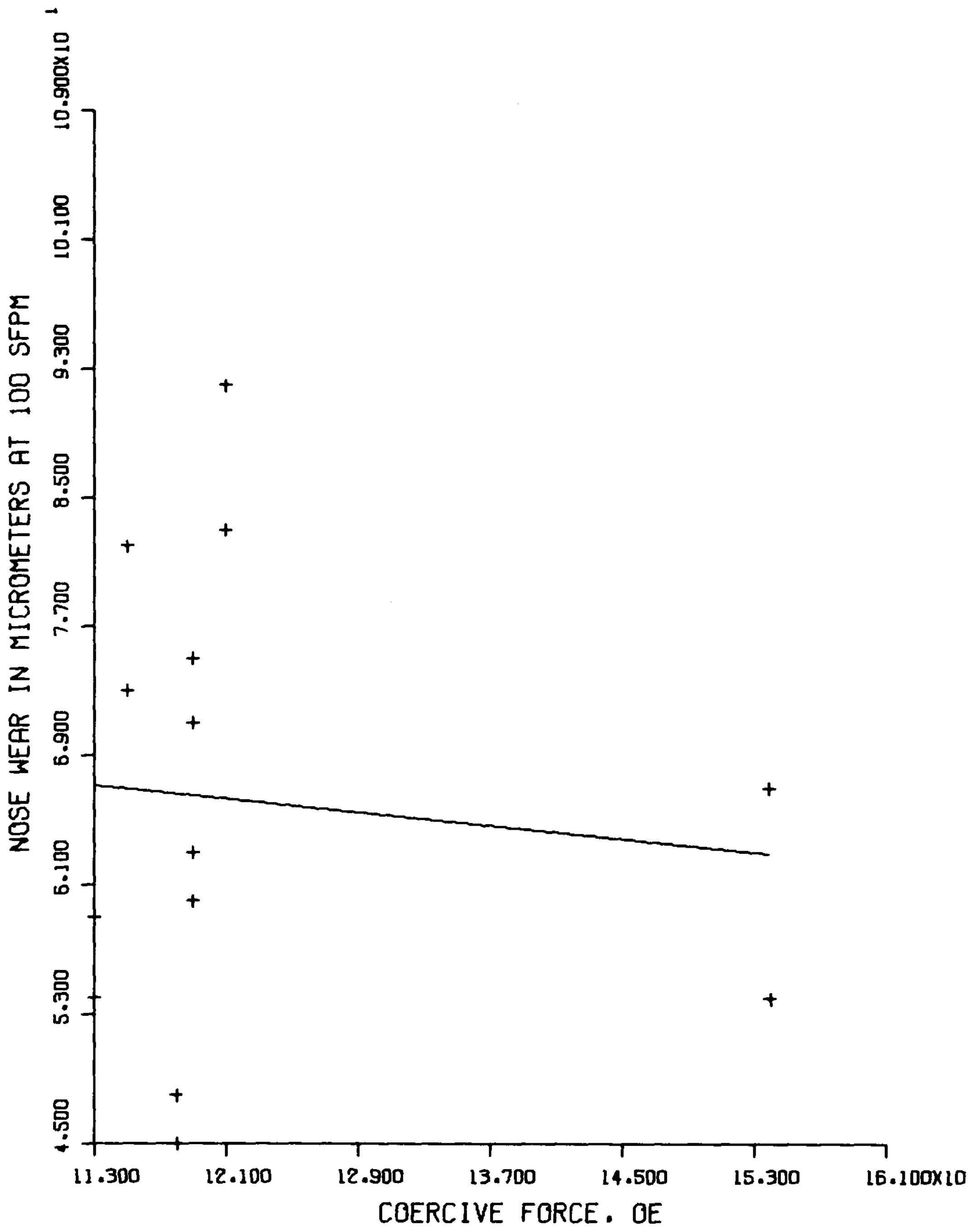
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 64



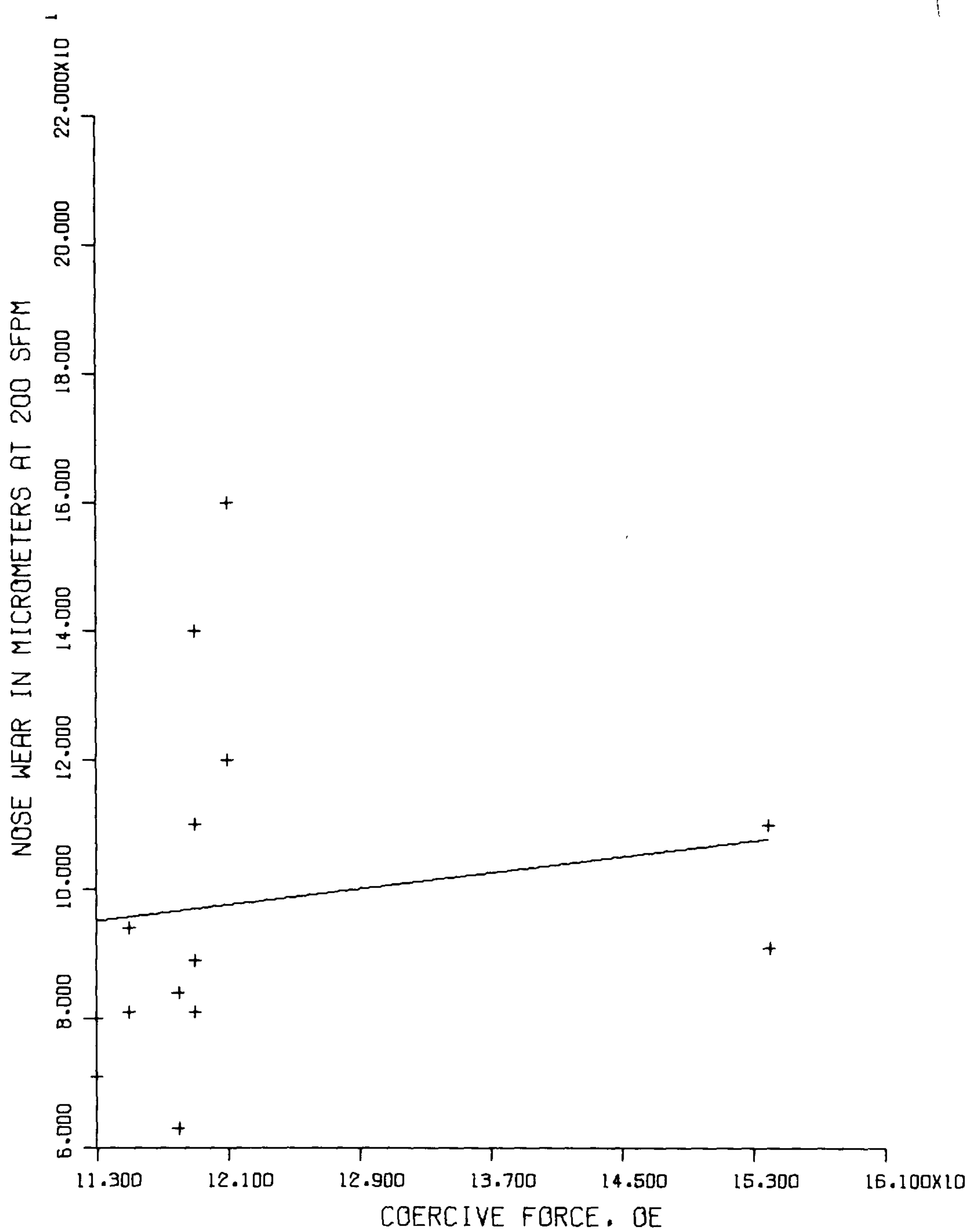
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 65



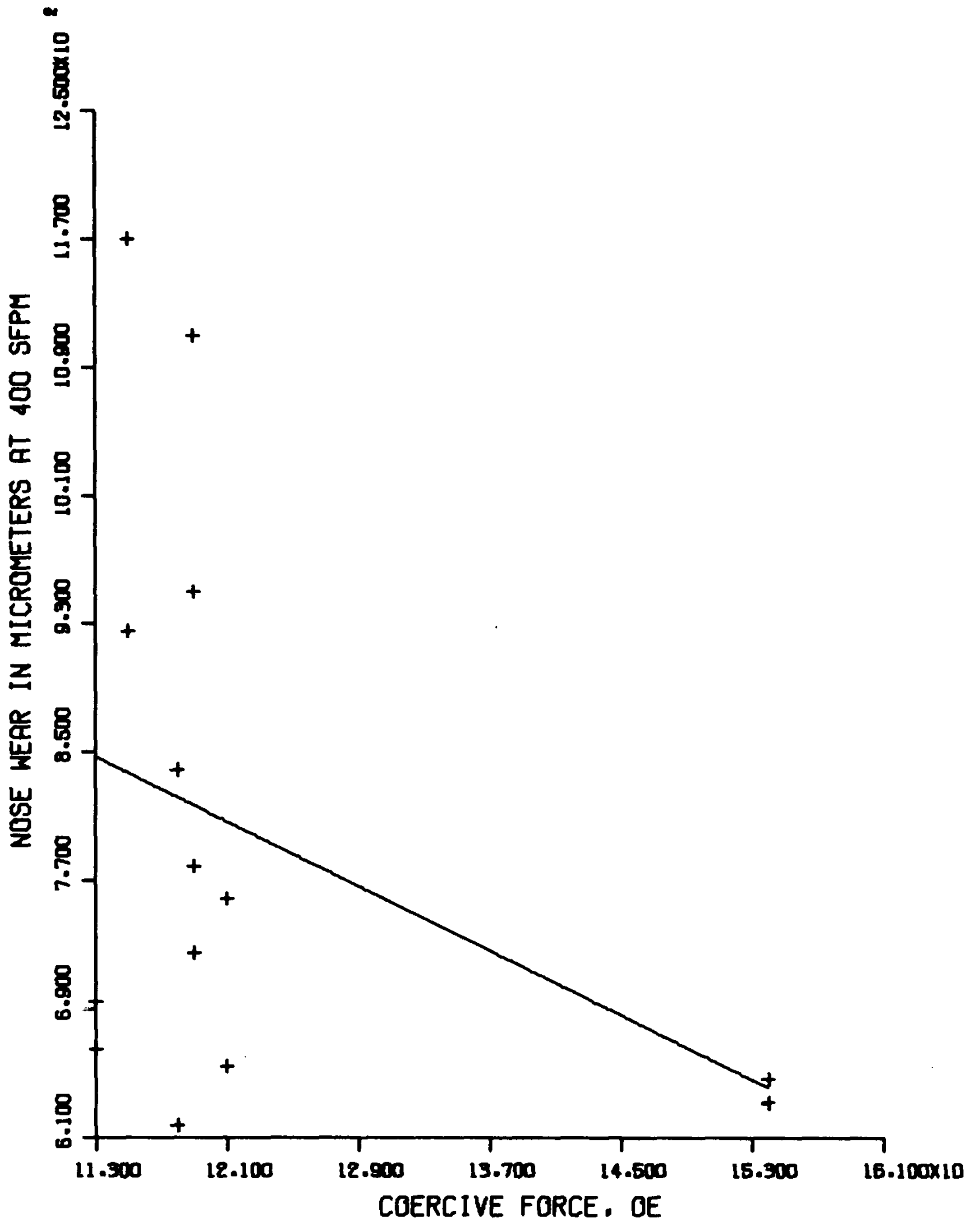
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 66



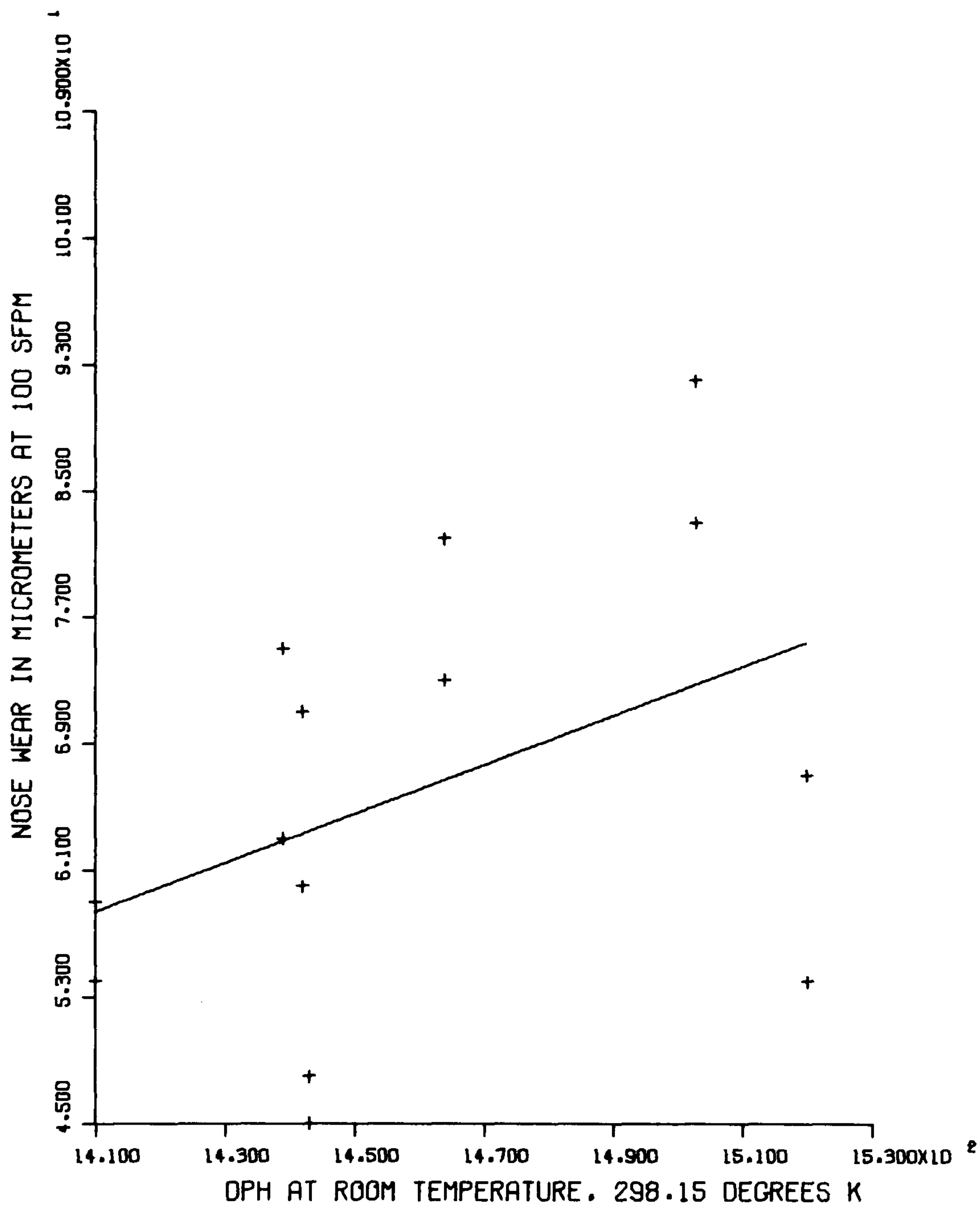
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 67



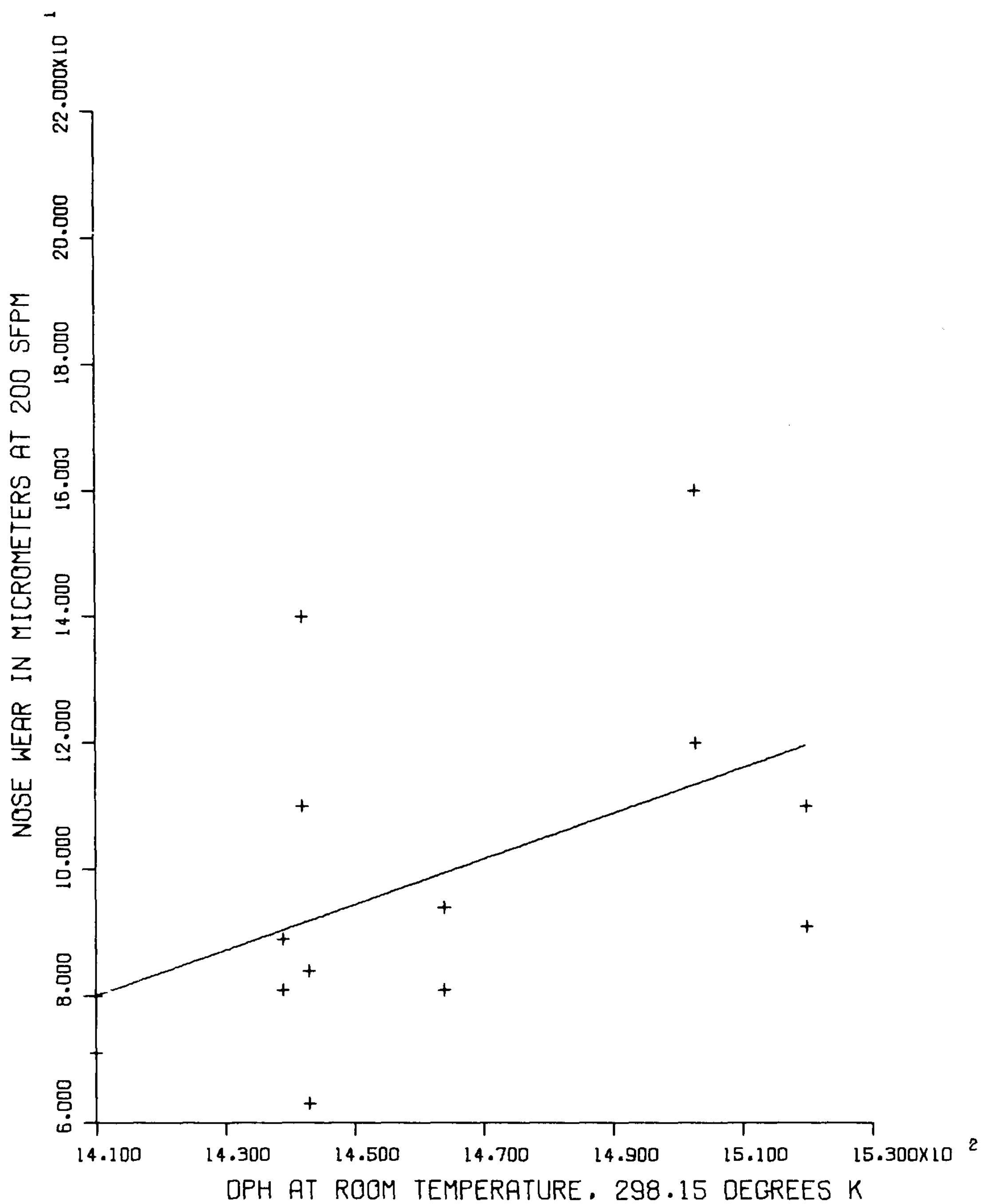
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 68



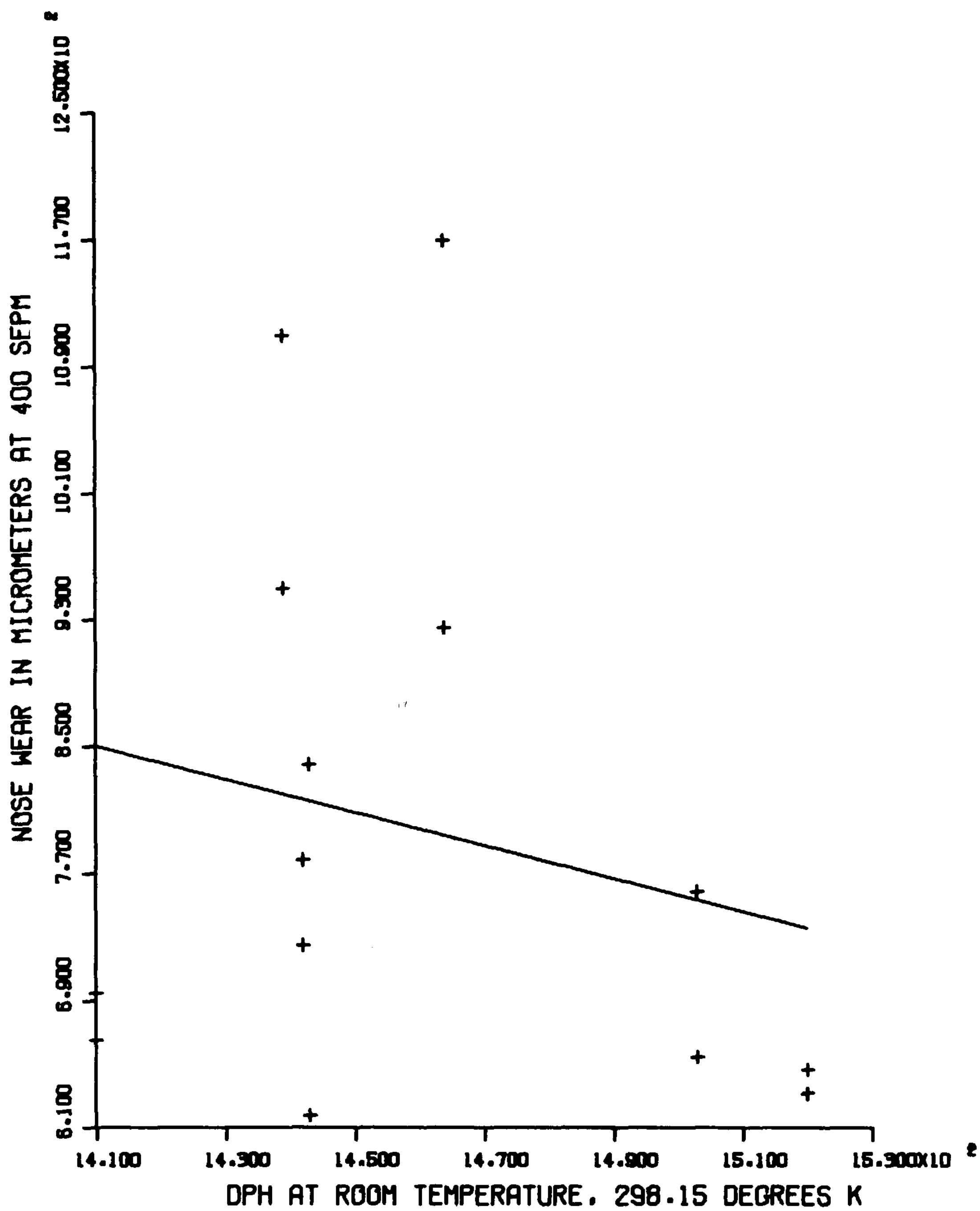
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 69



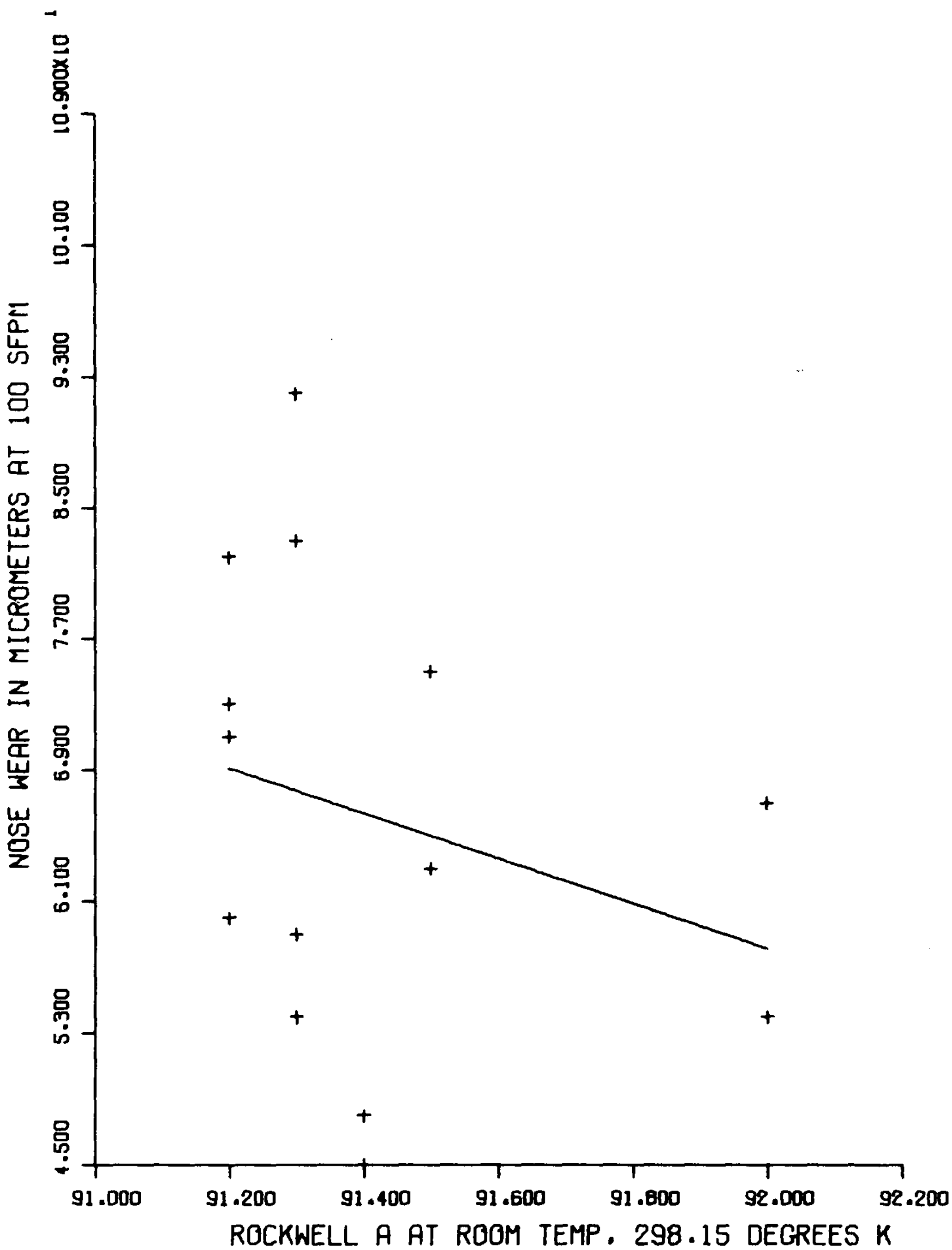
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 70



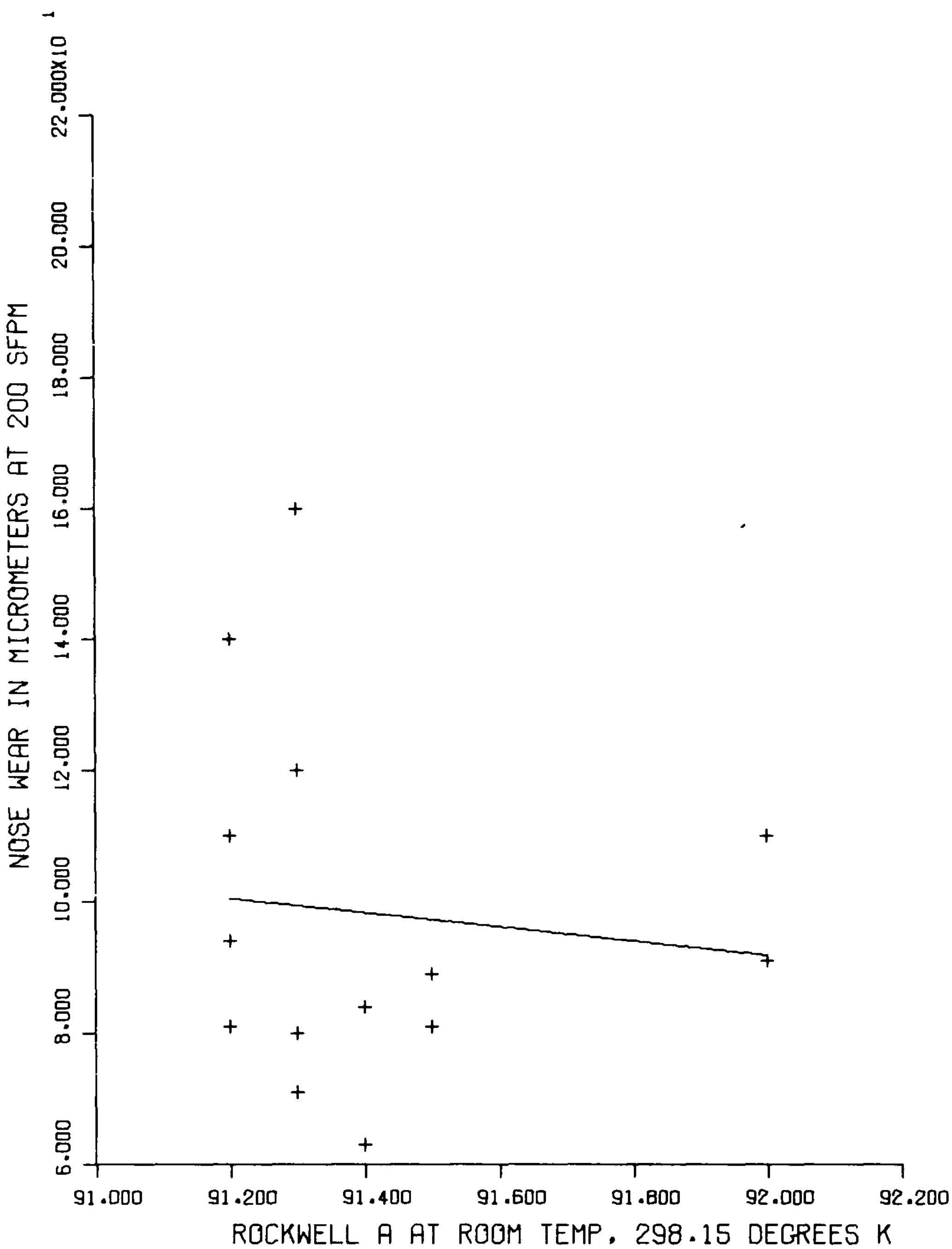
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 71



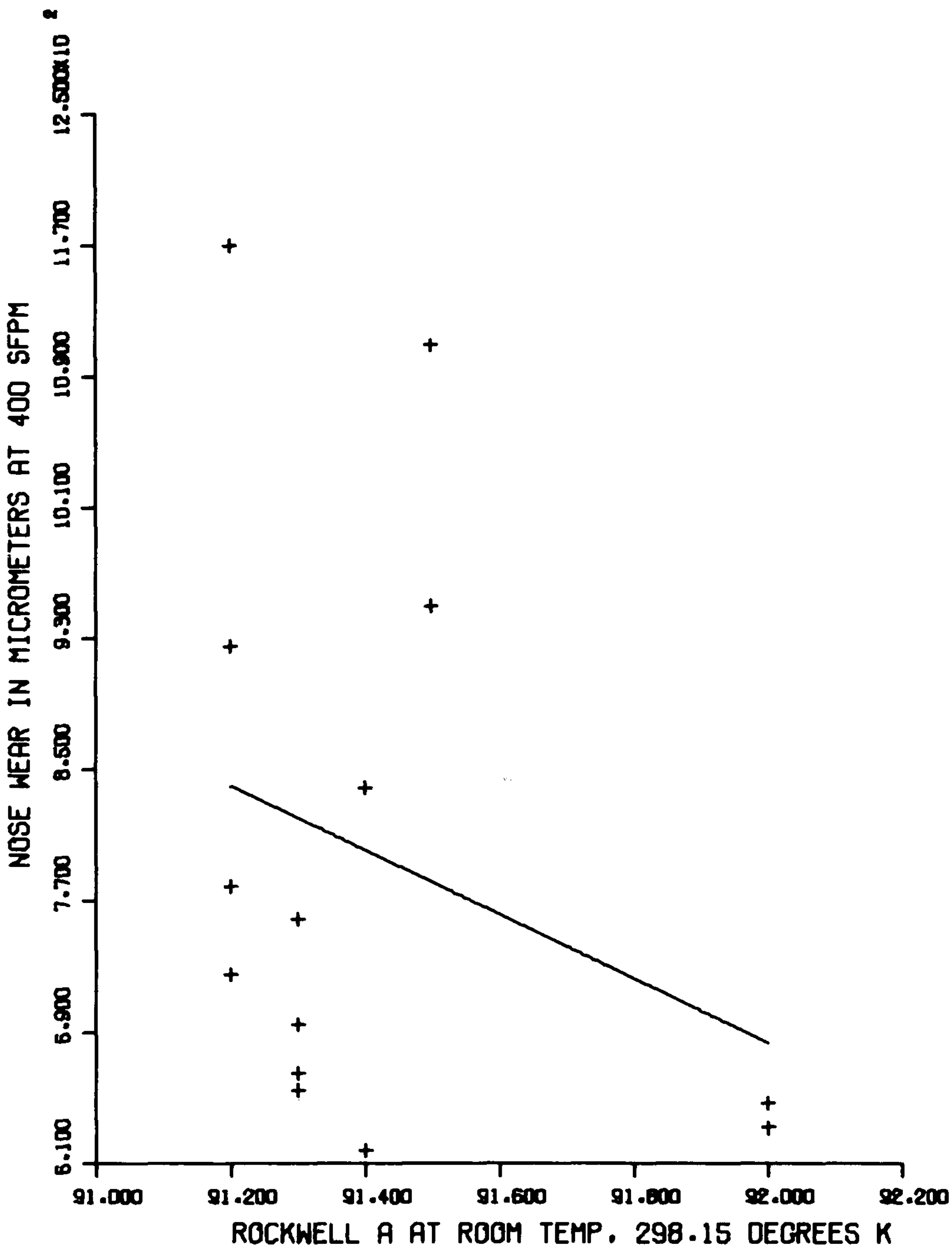
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 72



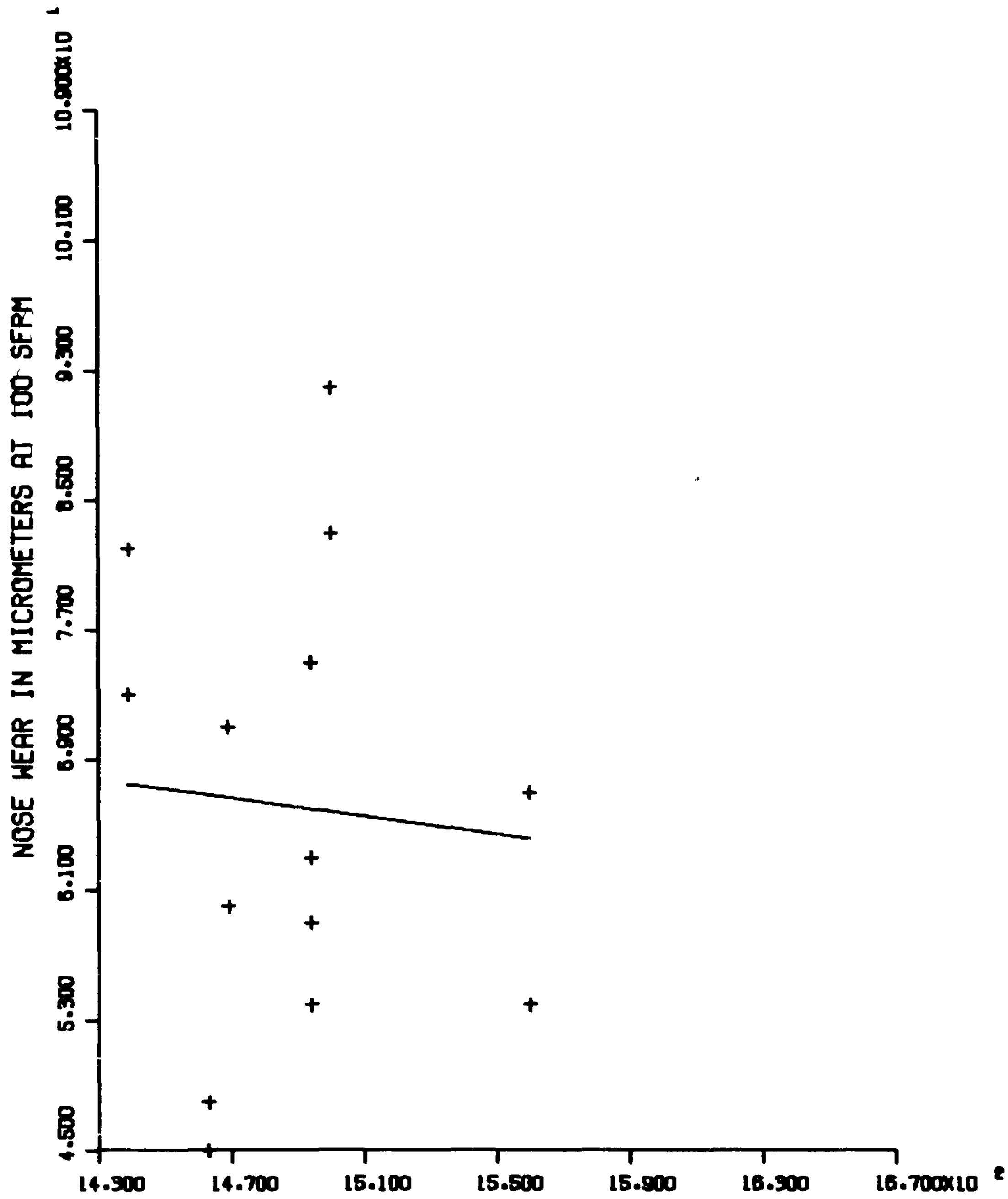
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 73



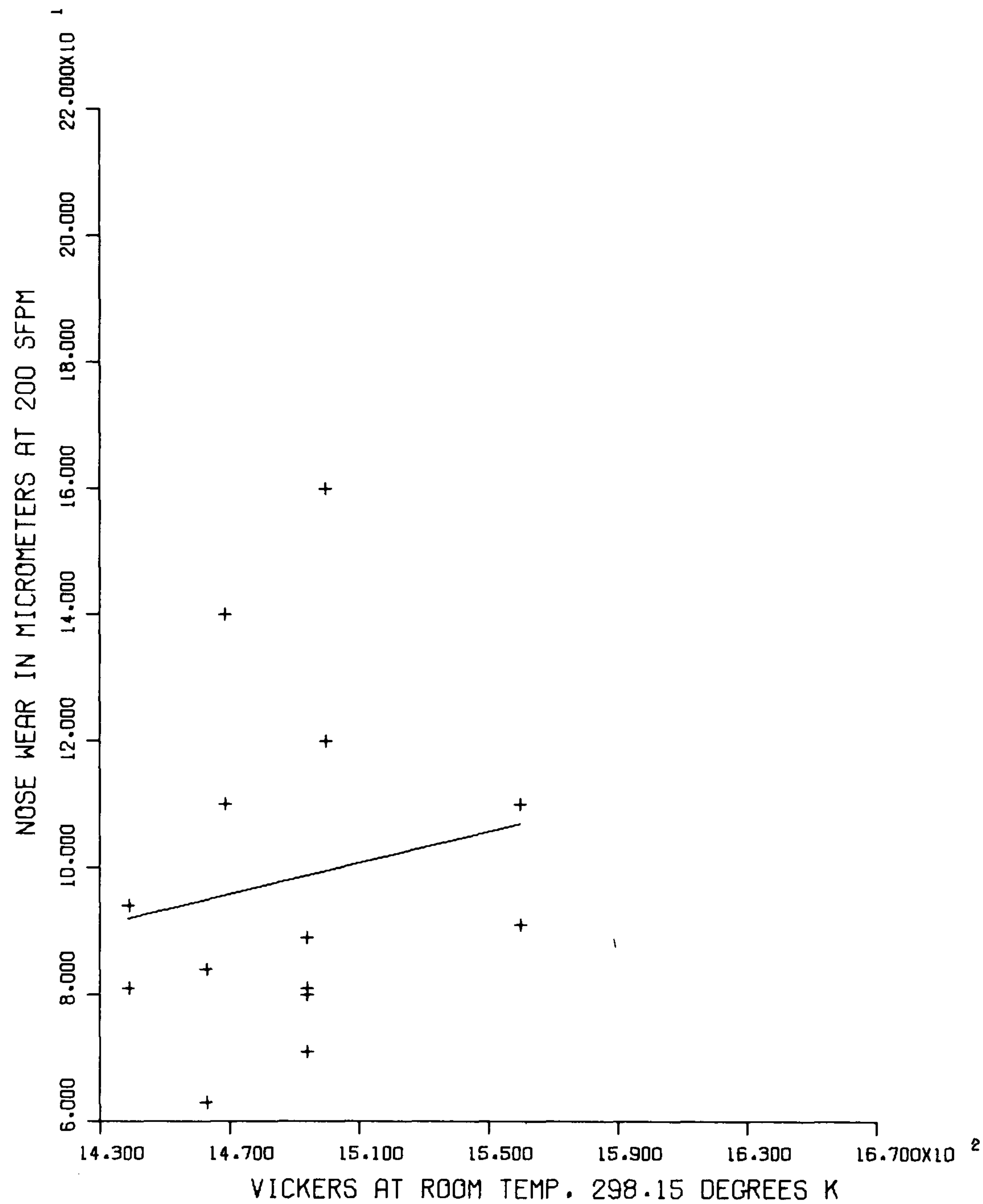
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 74



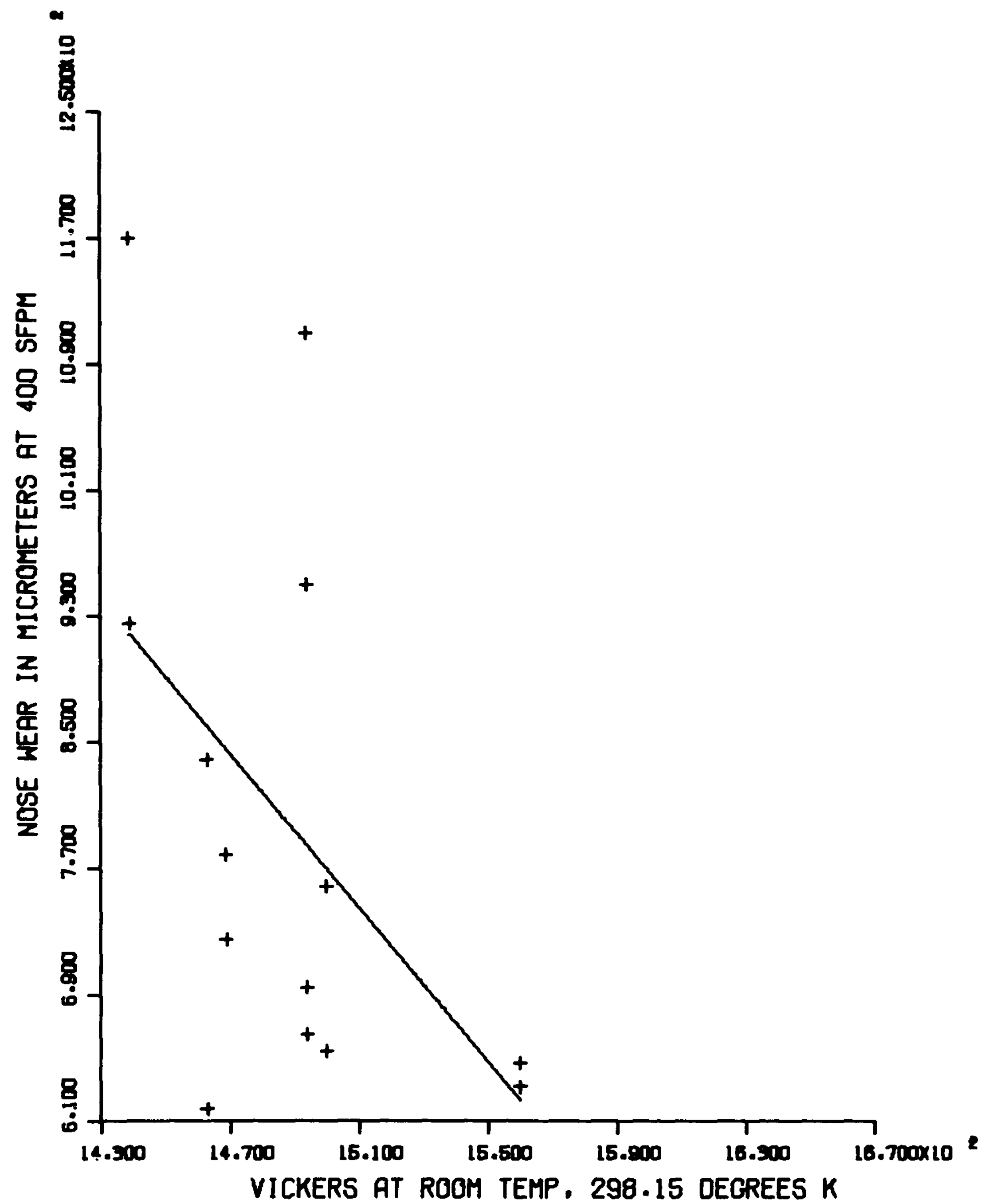
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 75



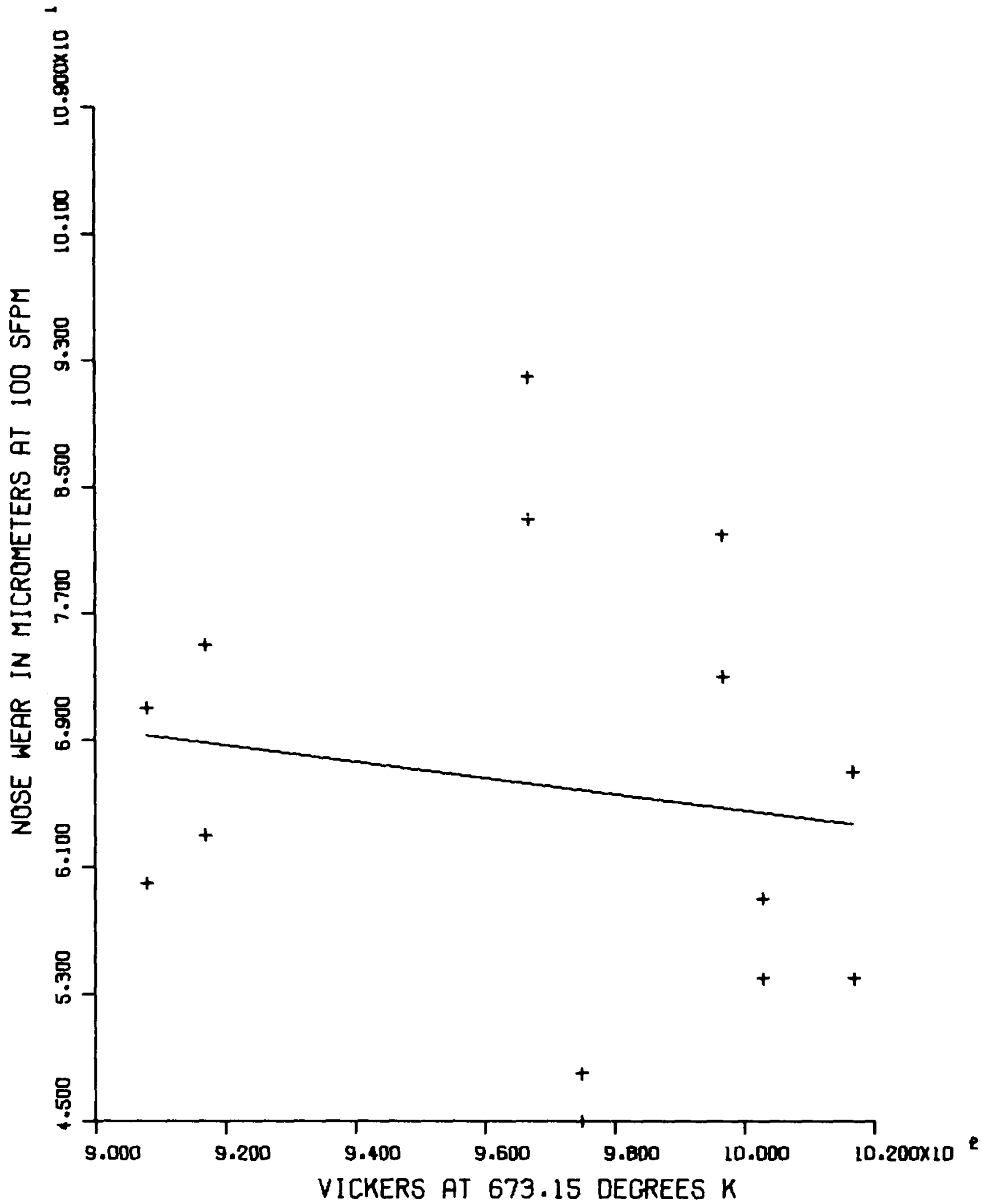
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 76



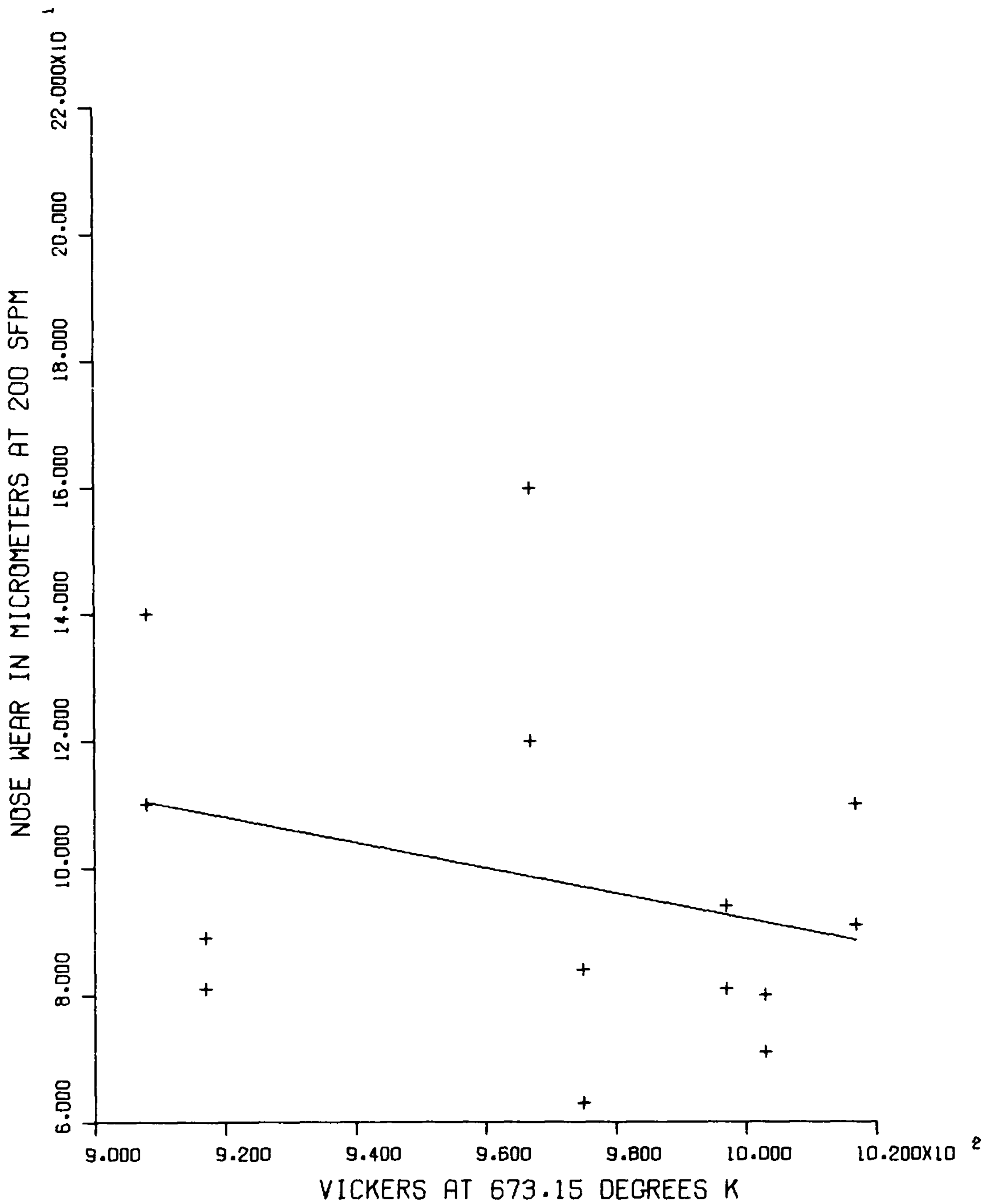
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 77



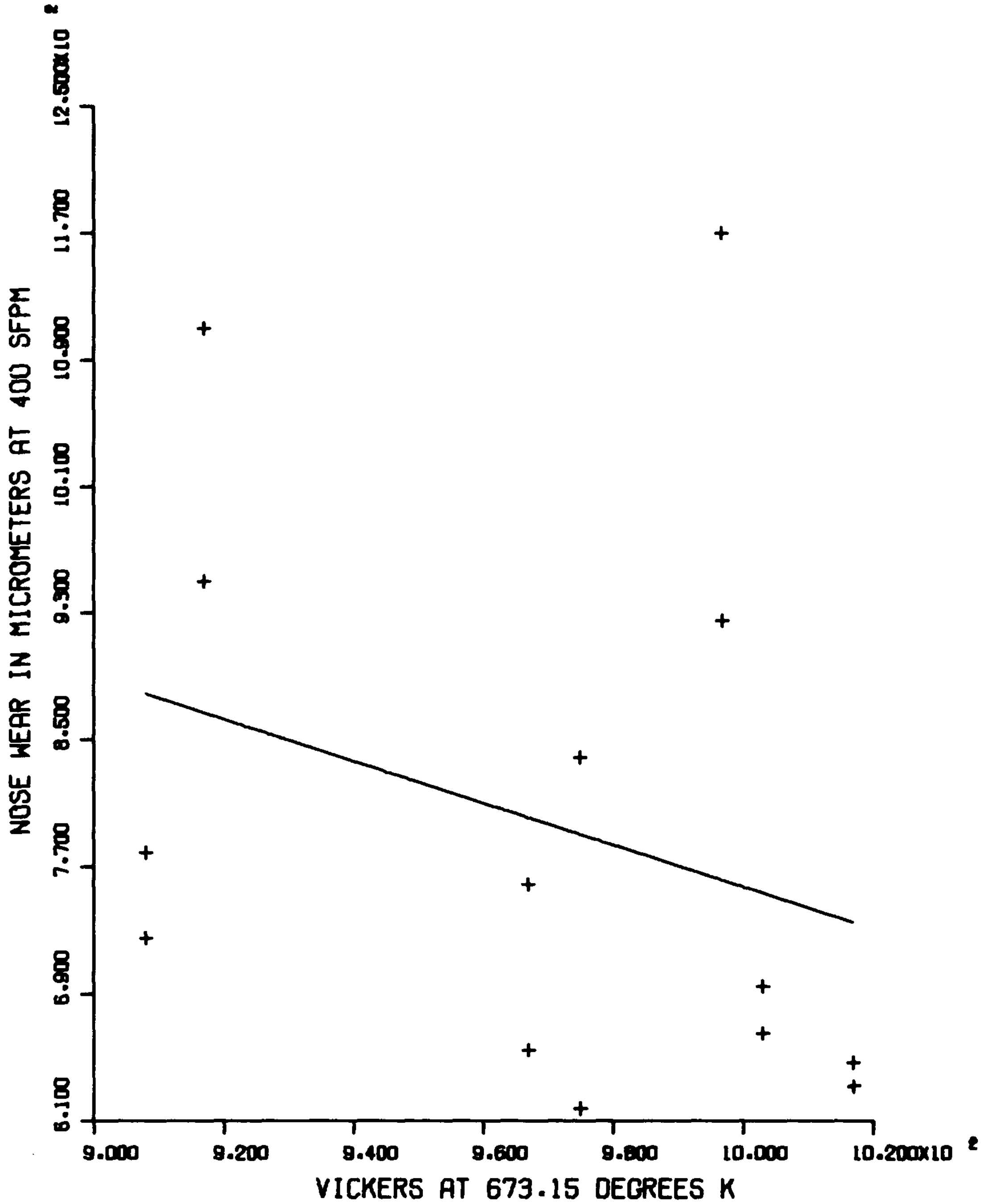
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 78



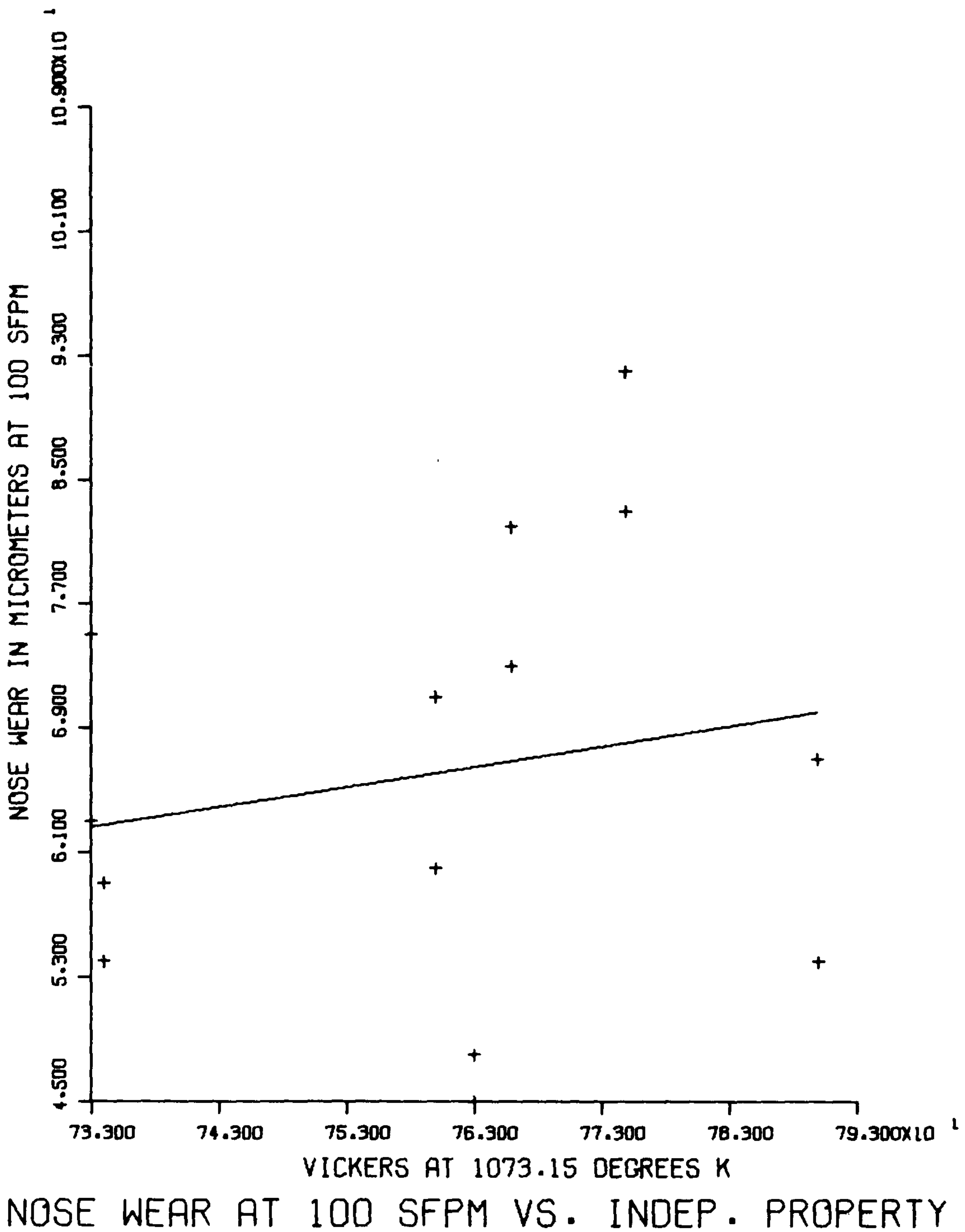
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 79



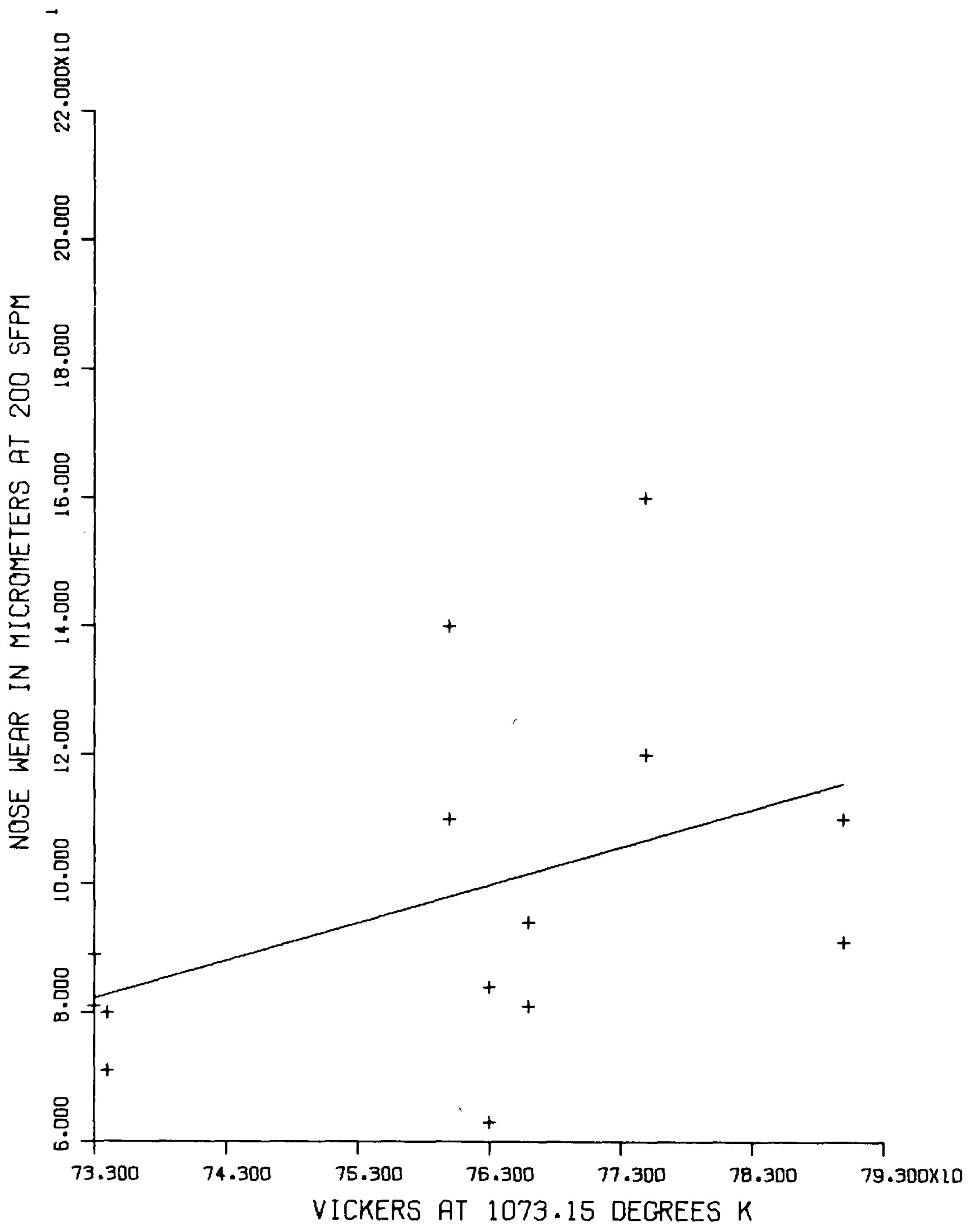
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 80



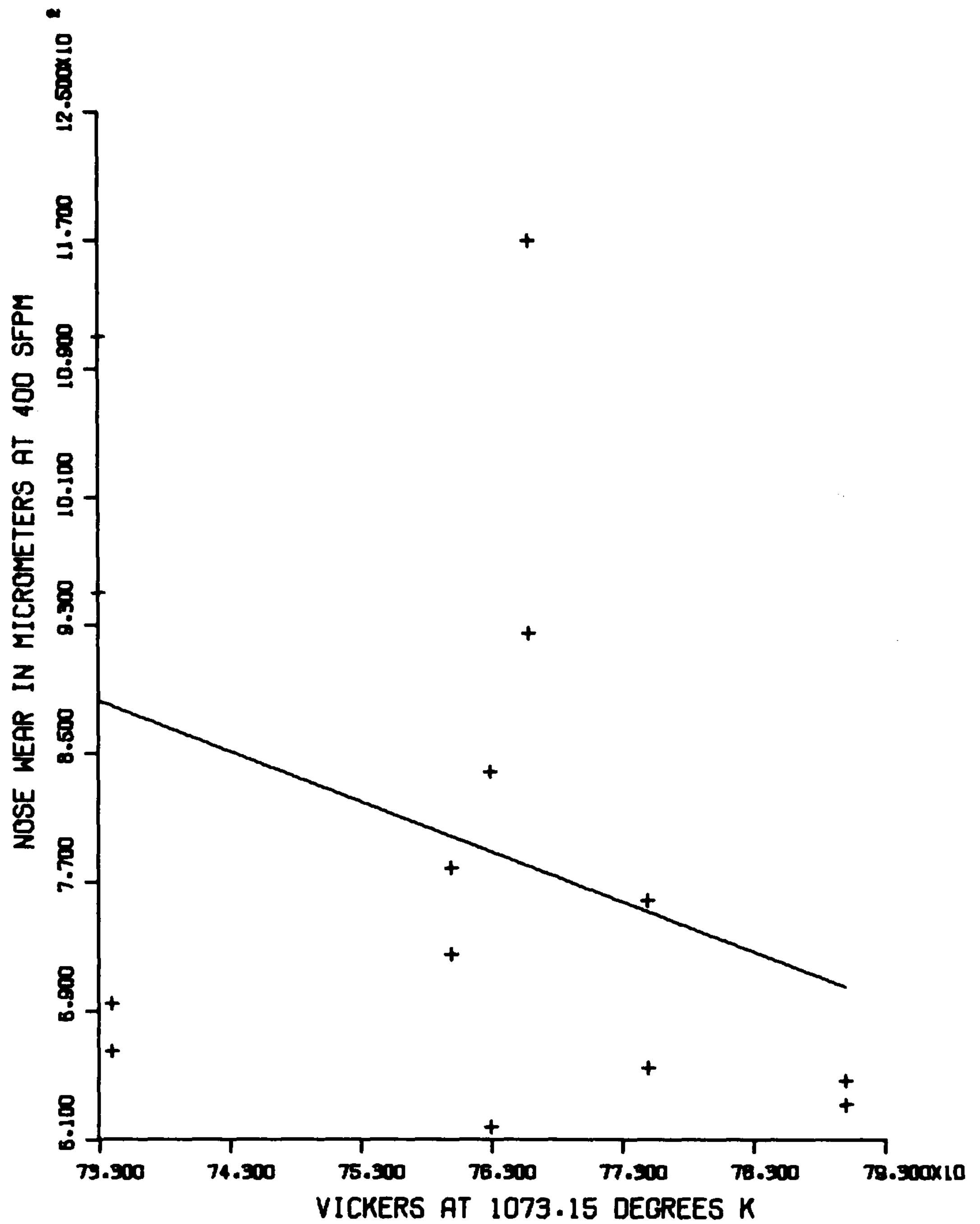
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 81



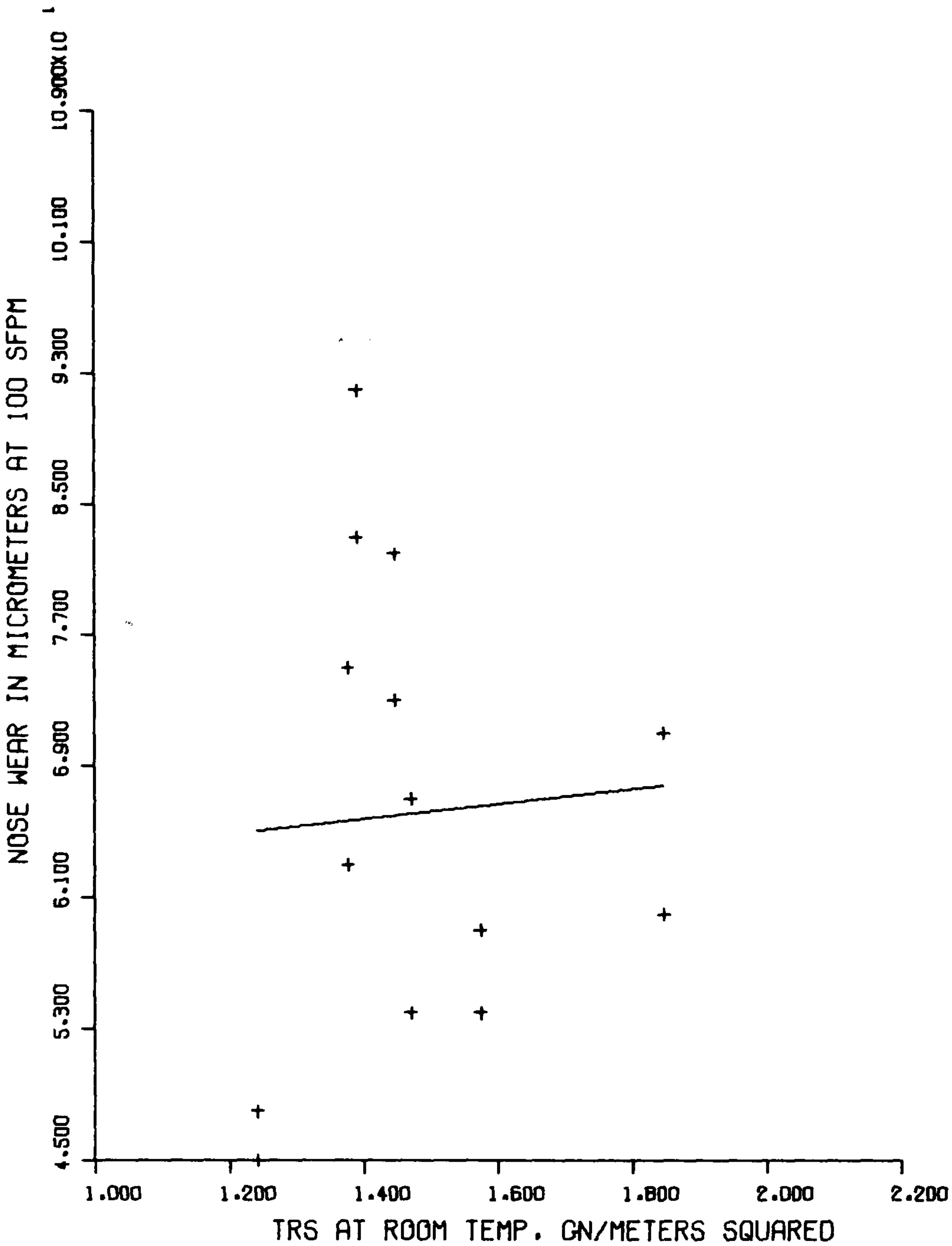
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 82



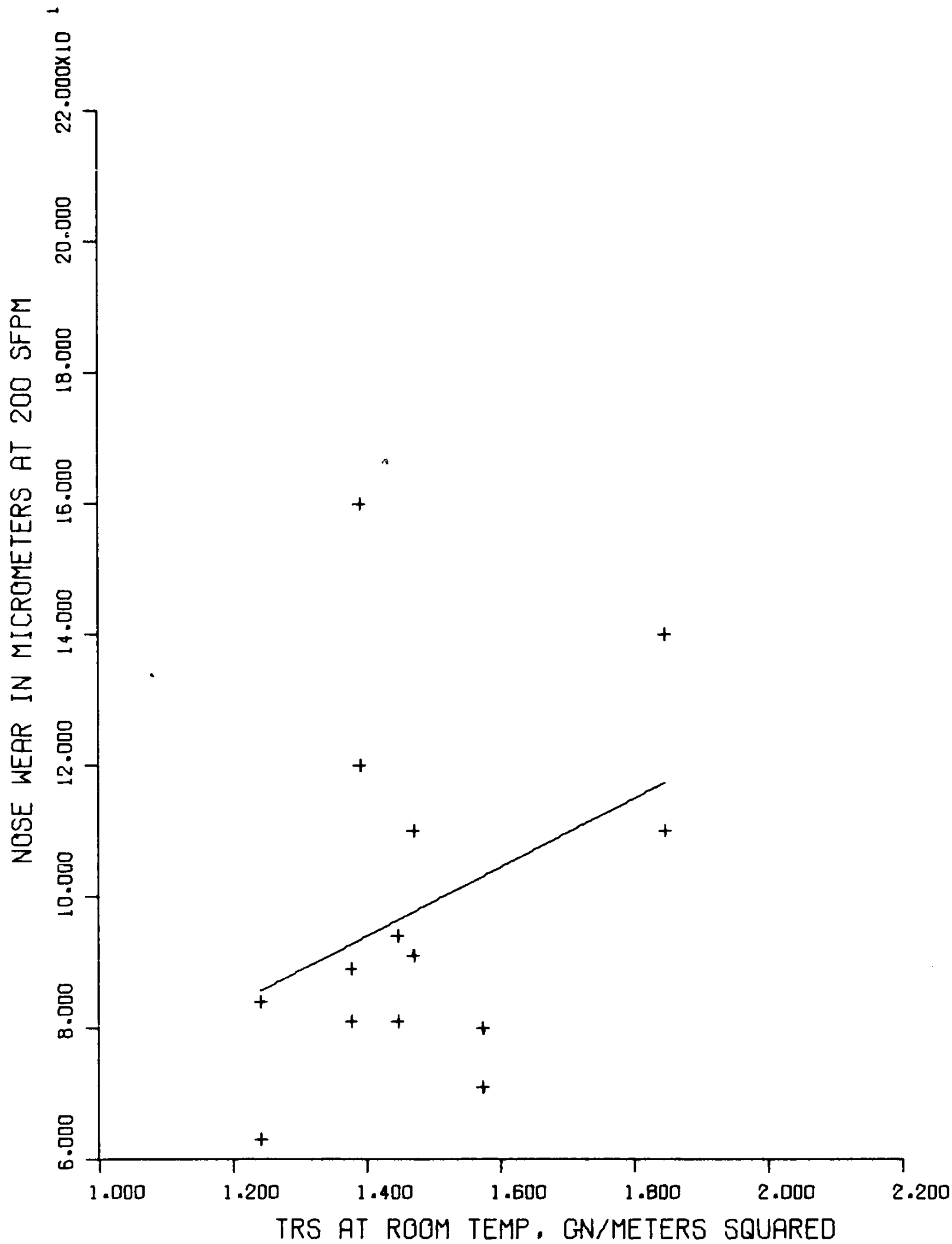
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 83



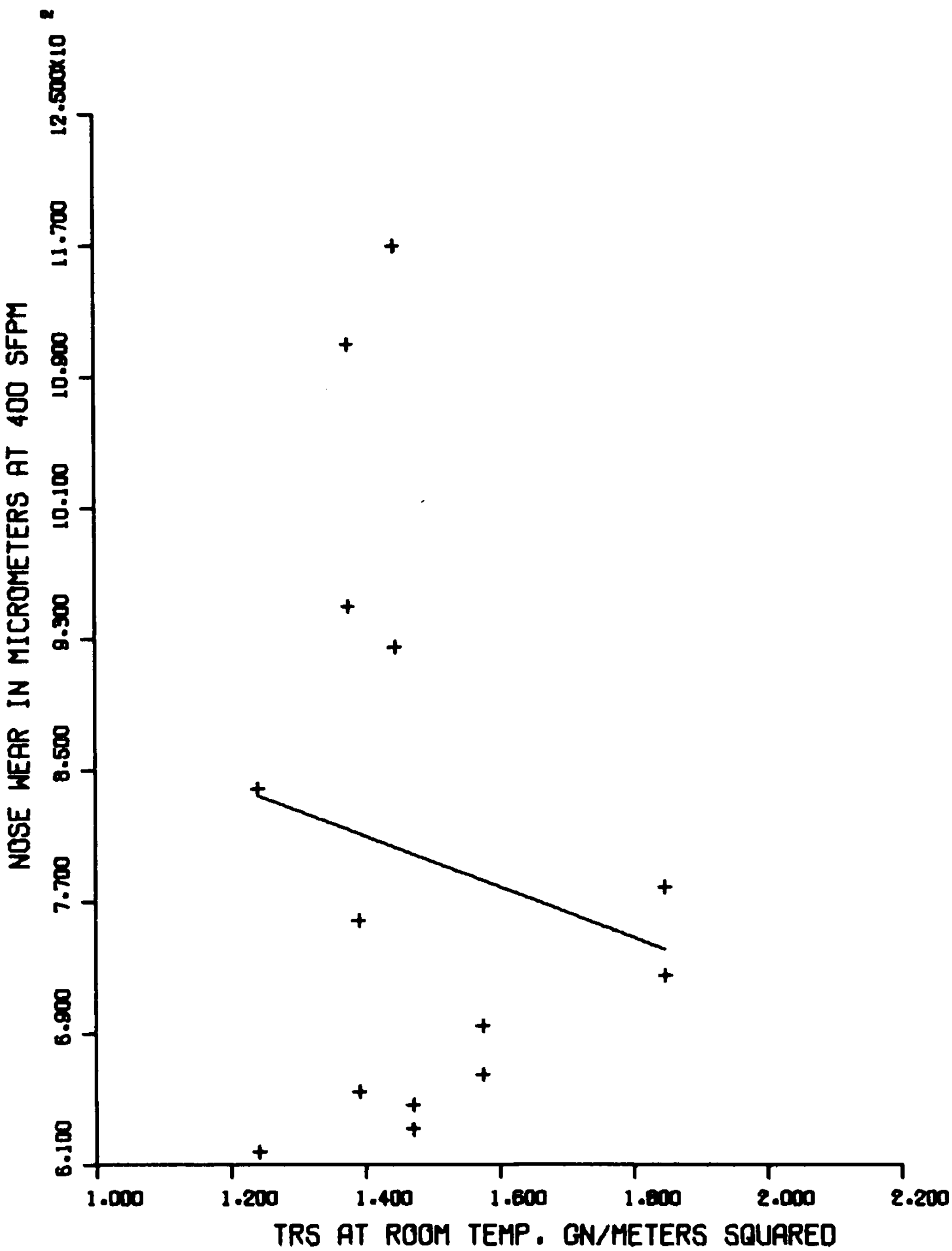
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 84



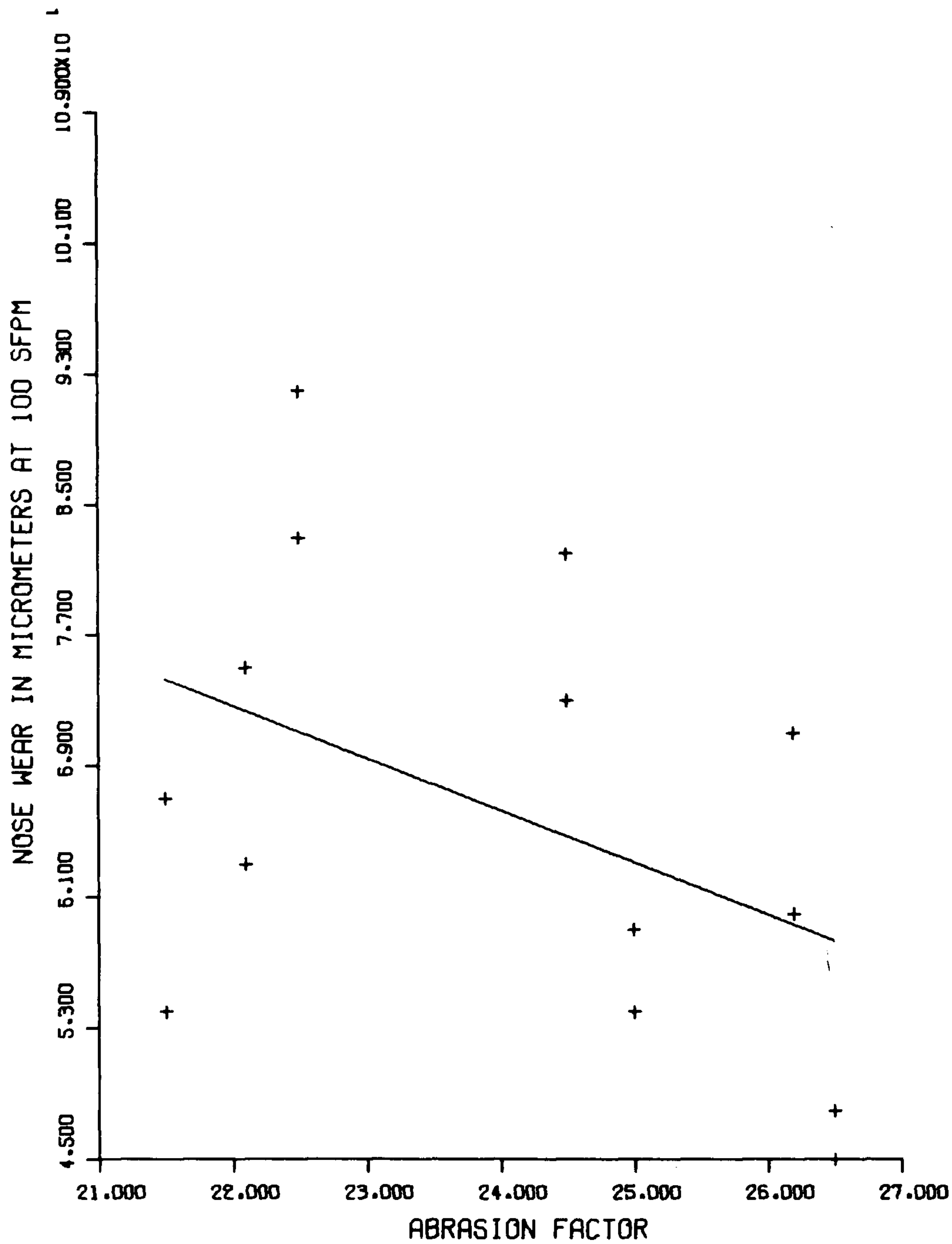
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 85



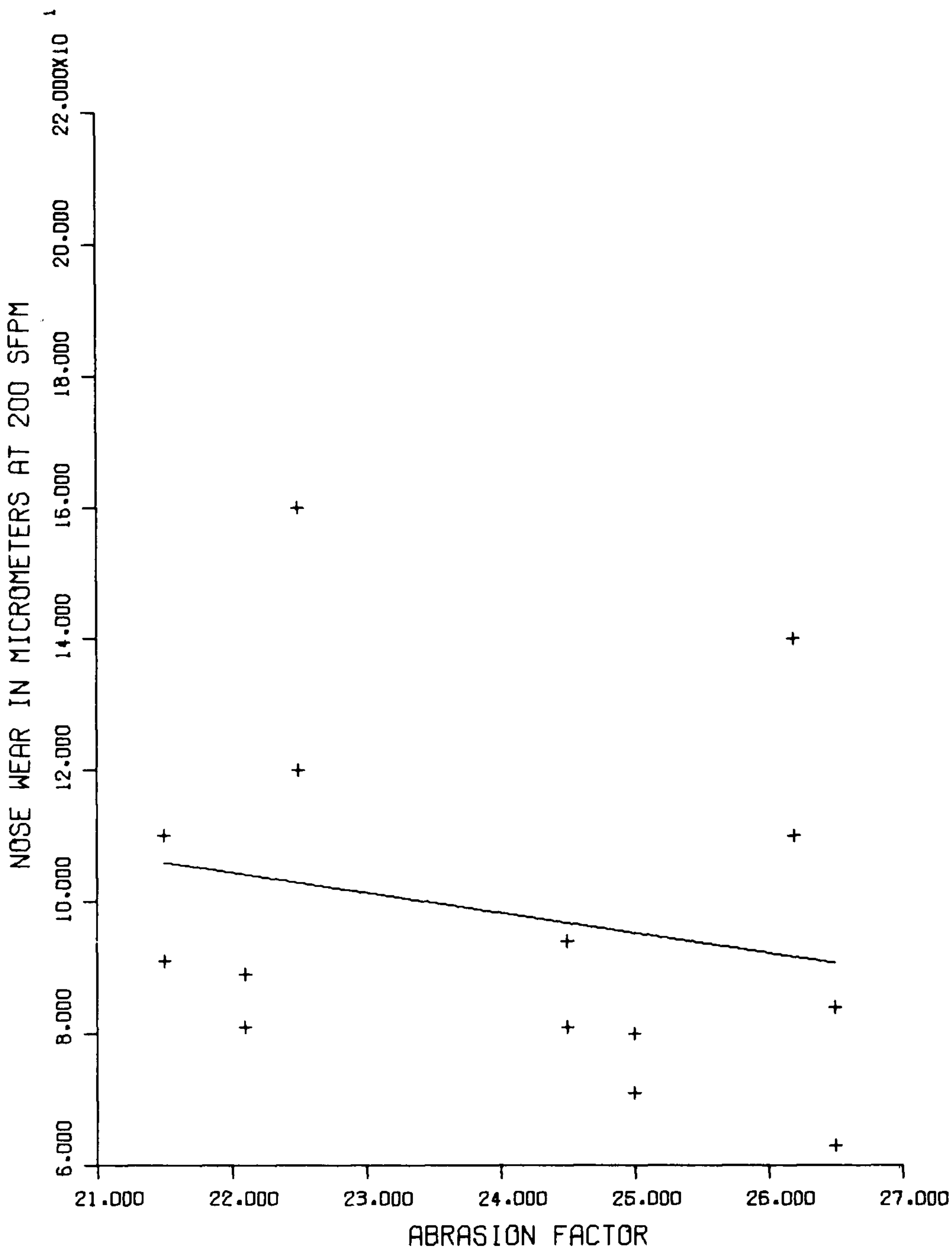
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 86



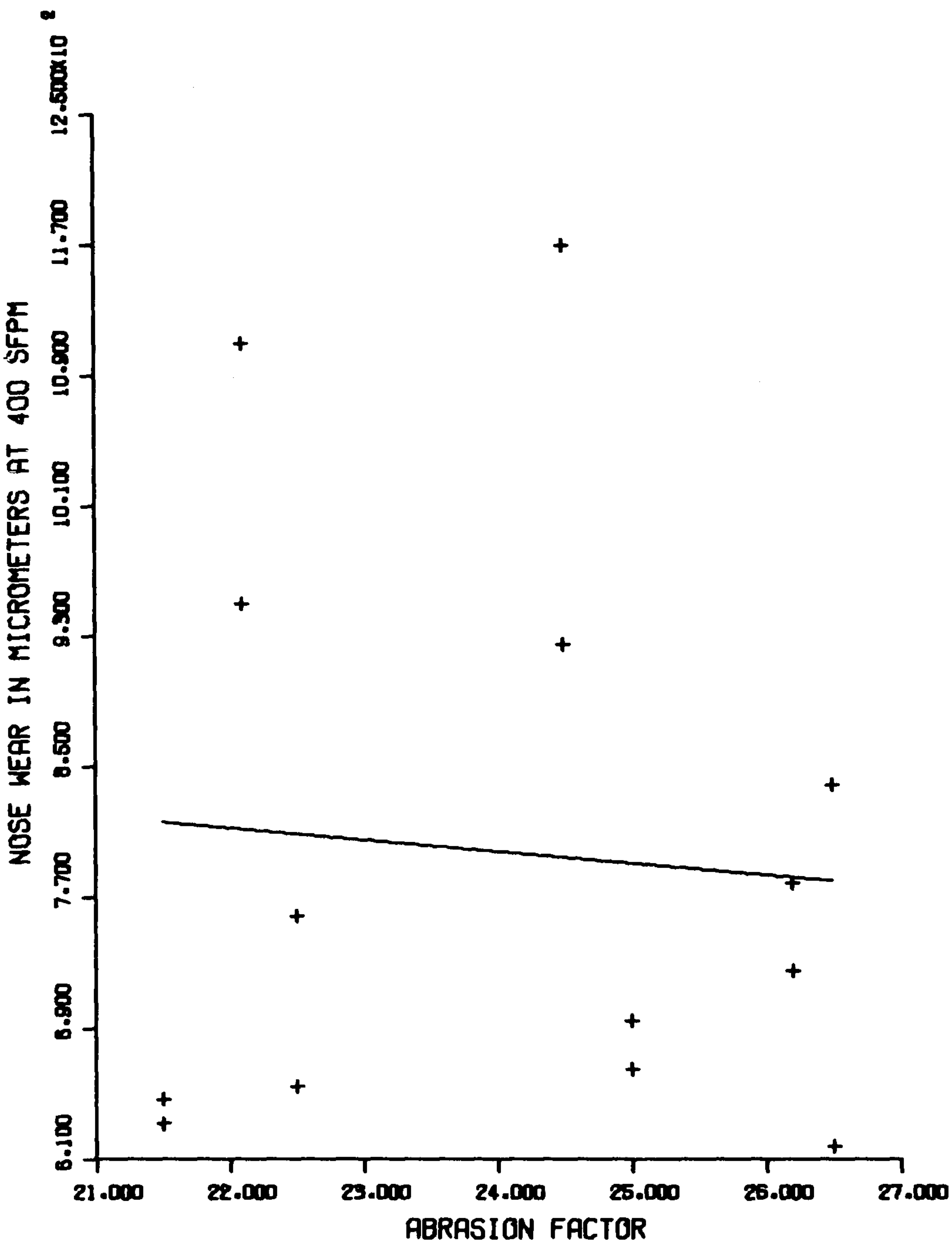
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 87



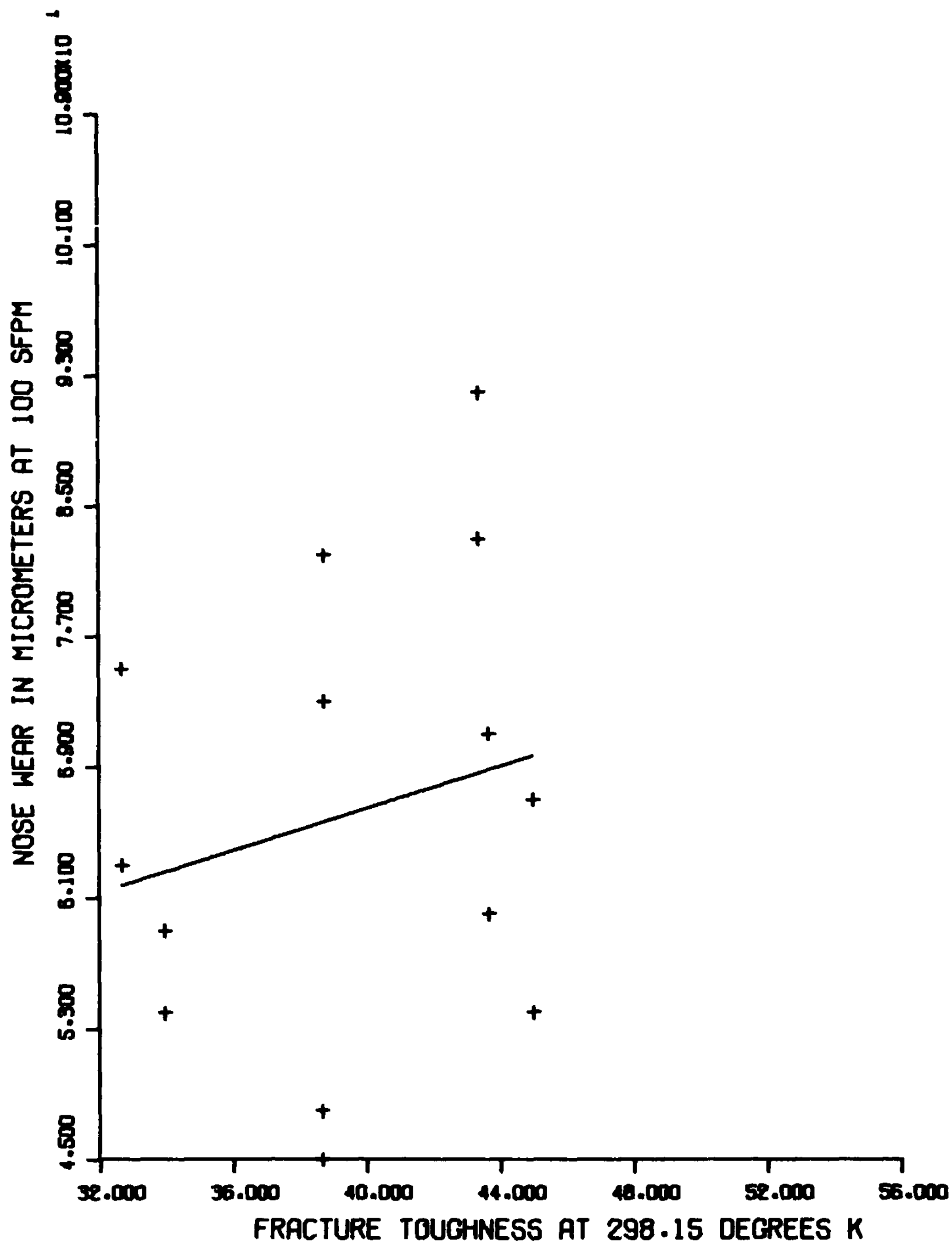
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 88



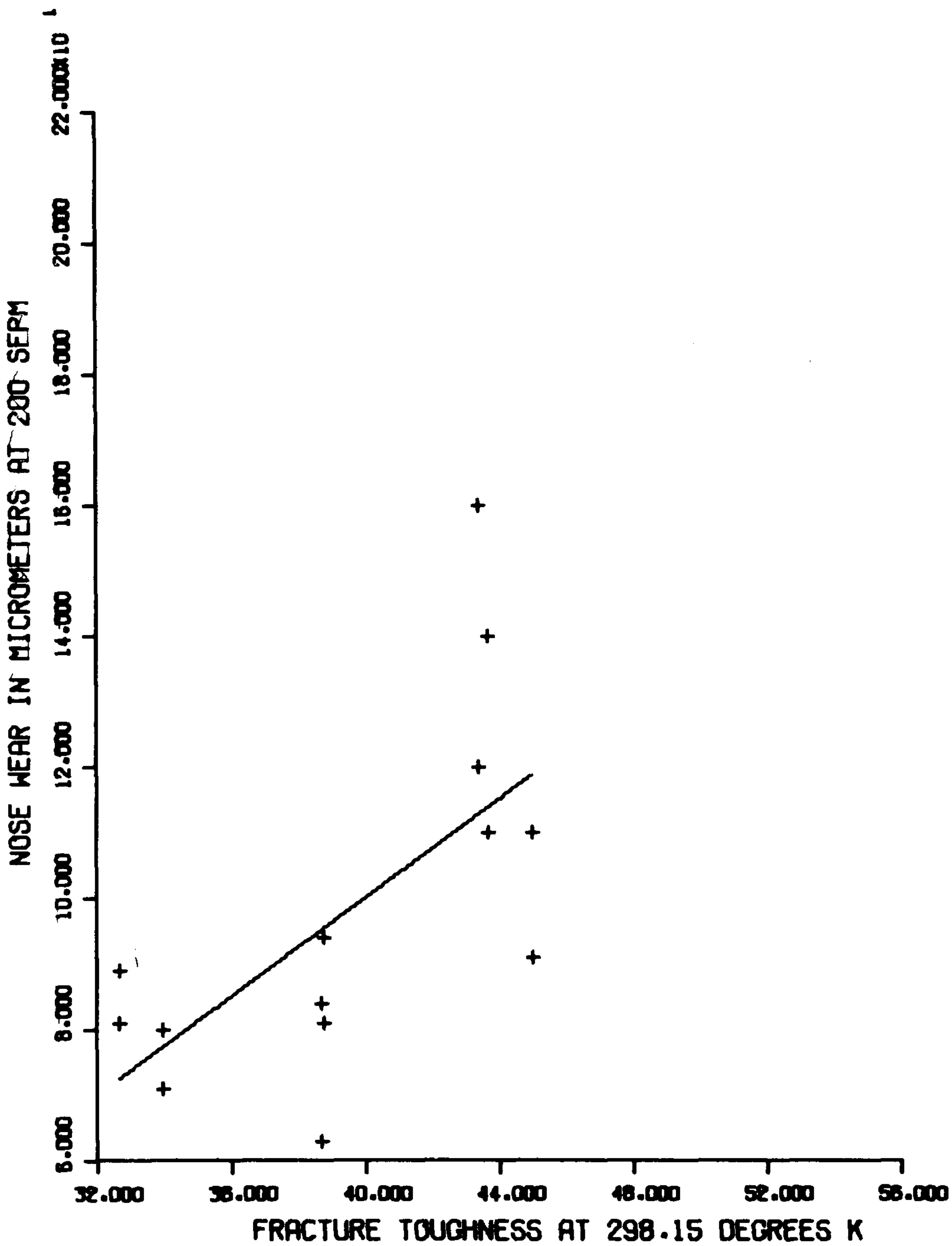
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 89



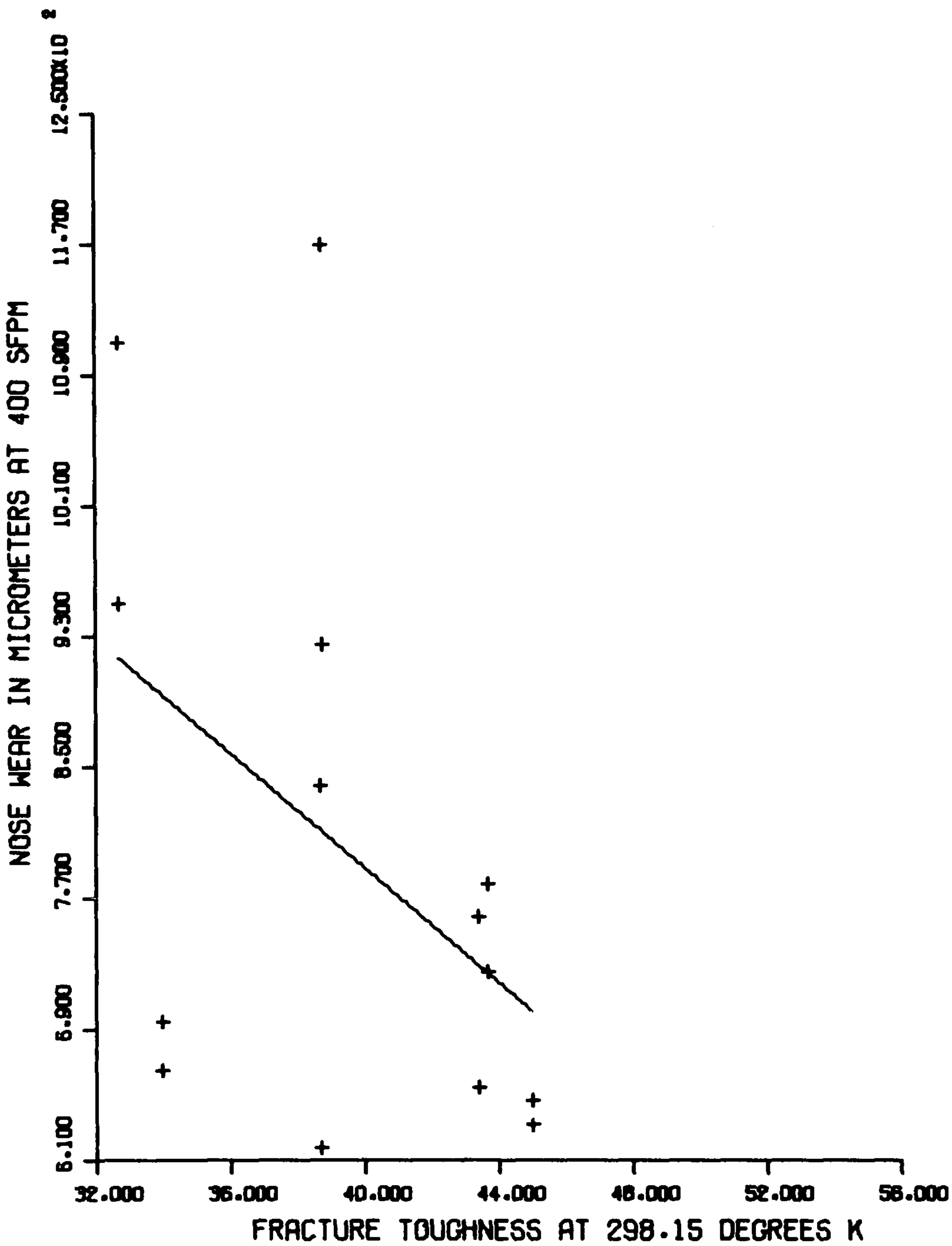
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 90



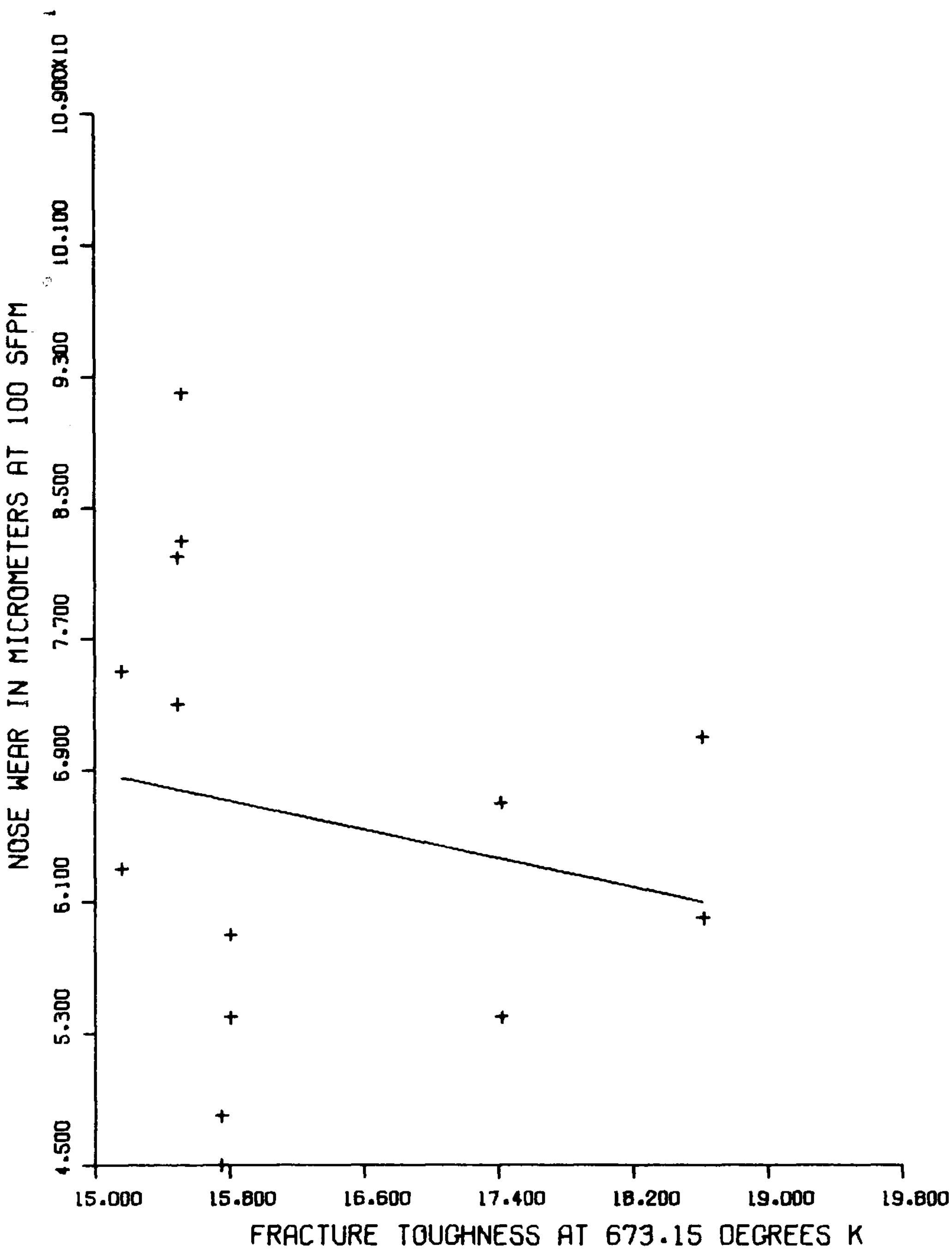
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 91



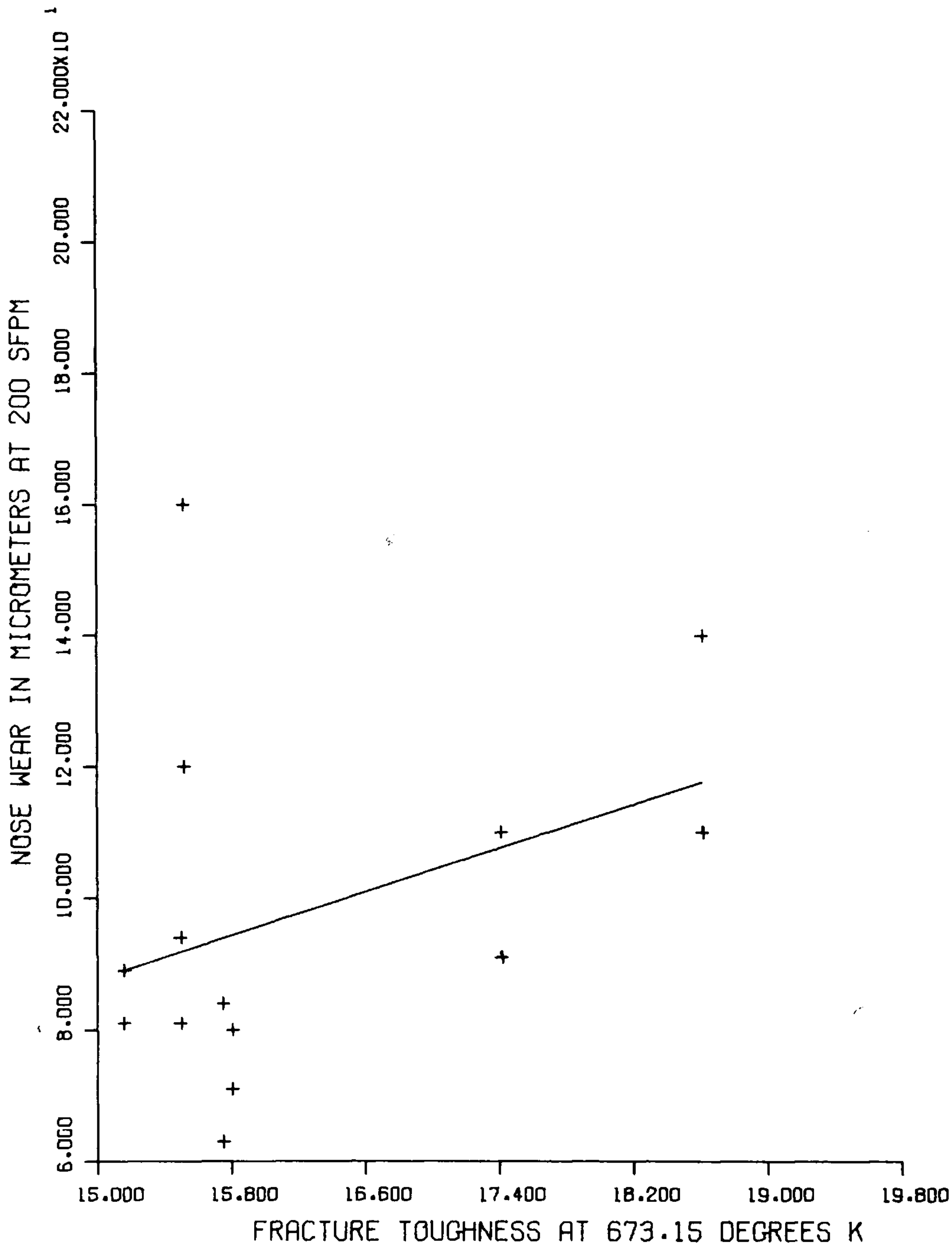
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 92



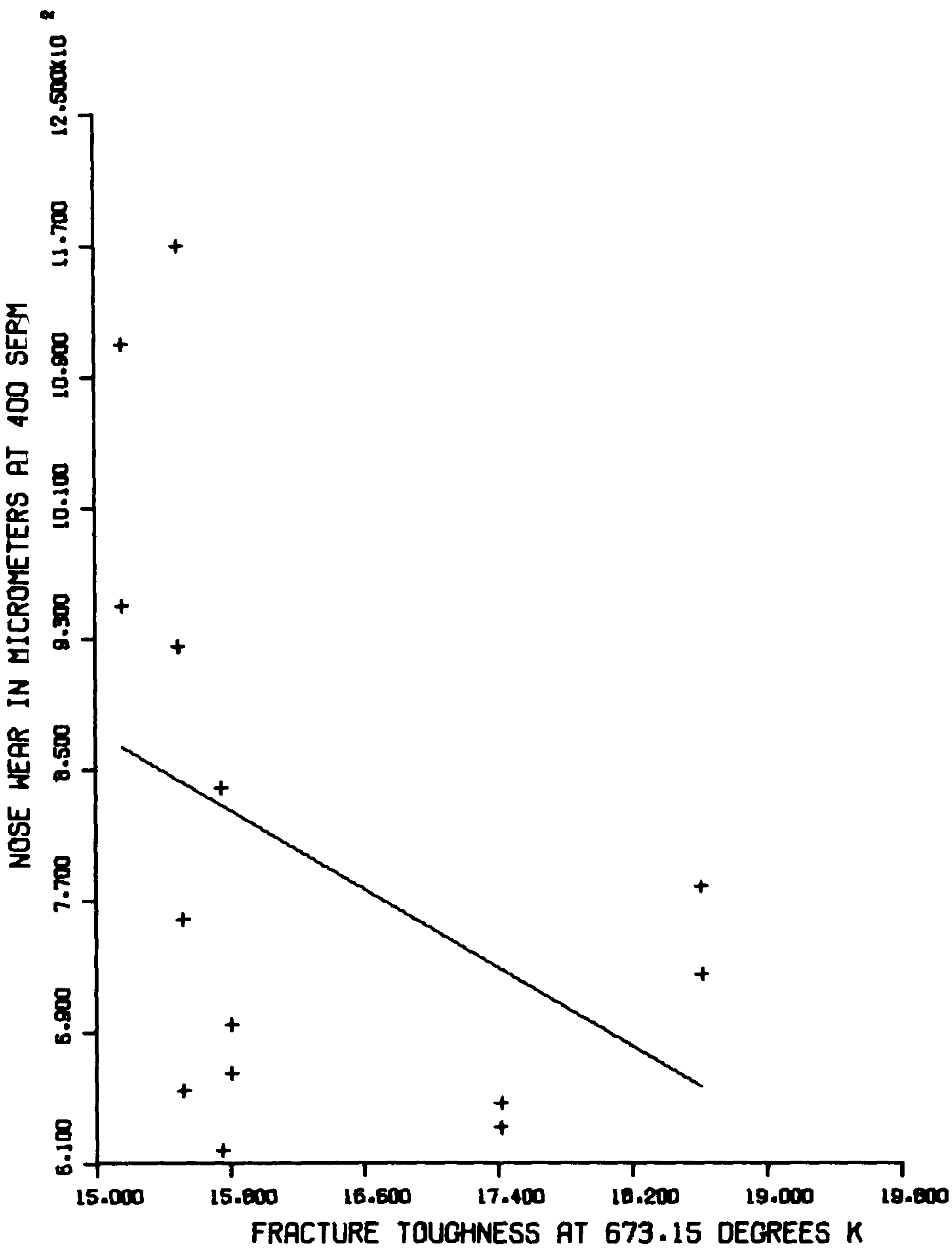
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 93



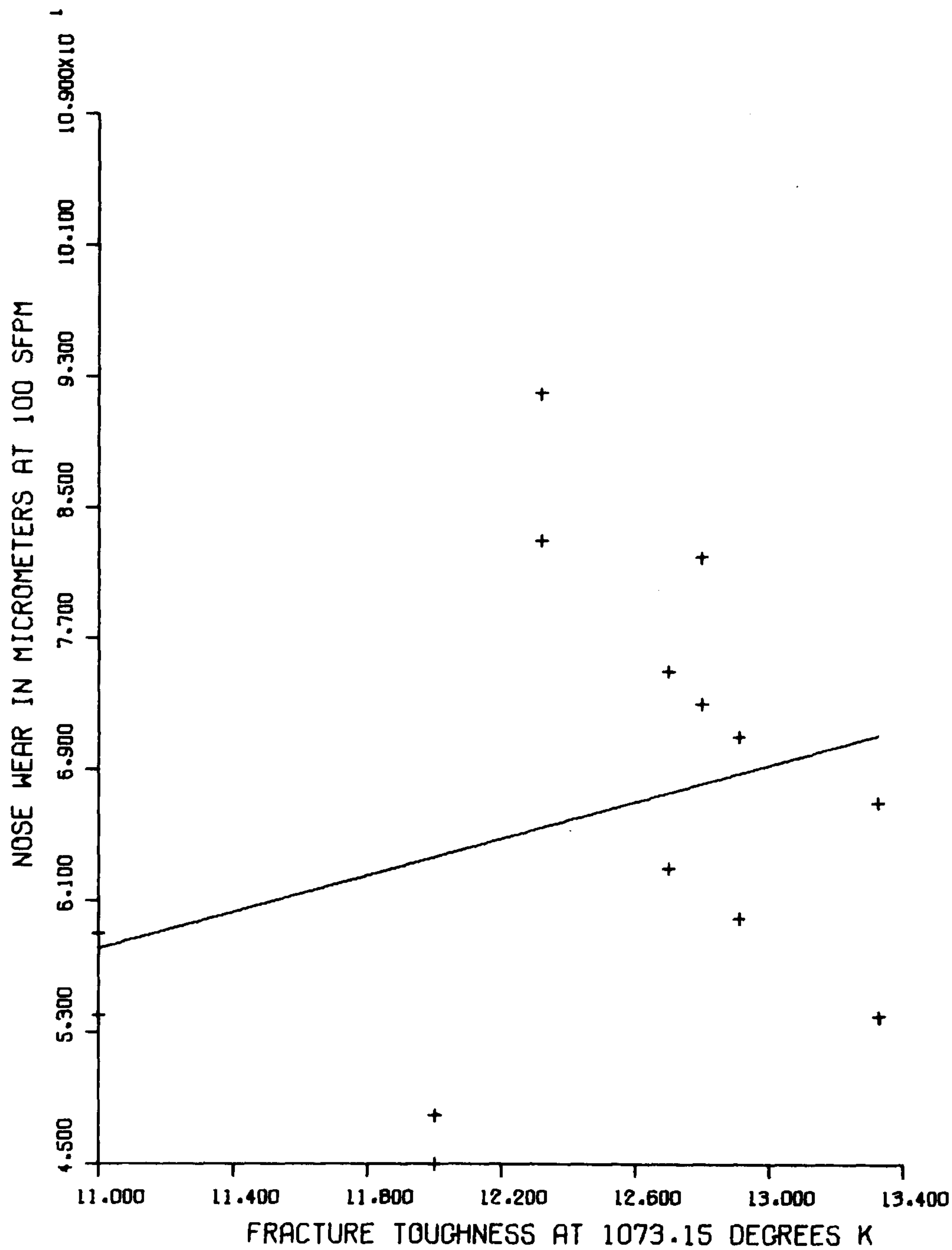
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 94



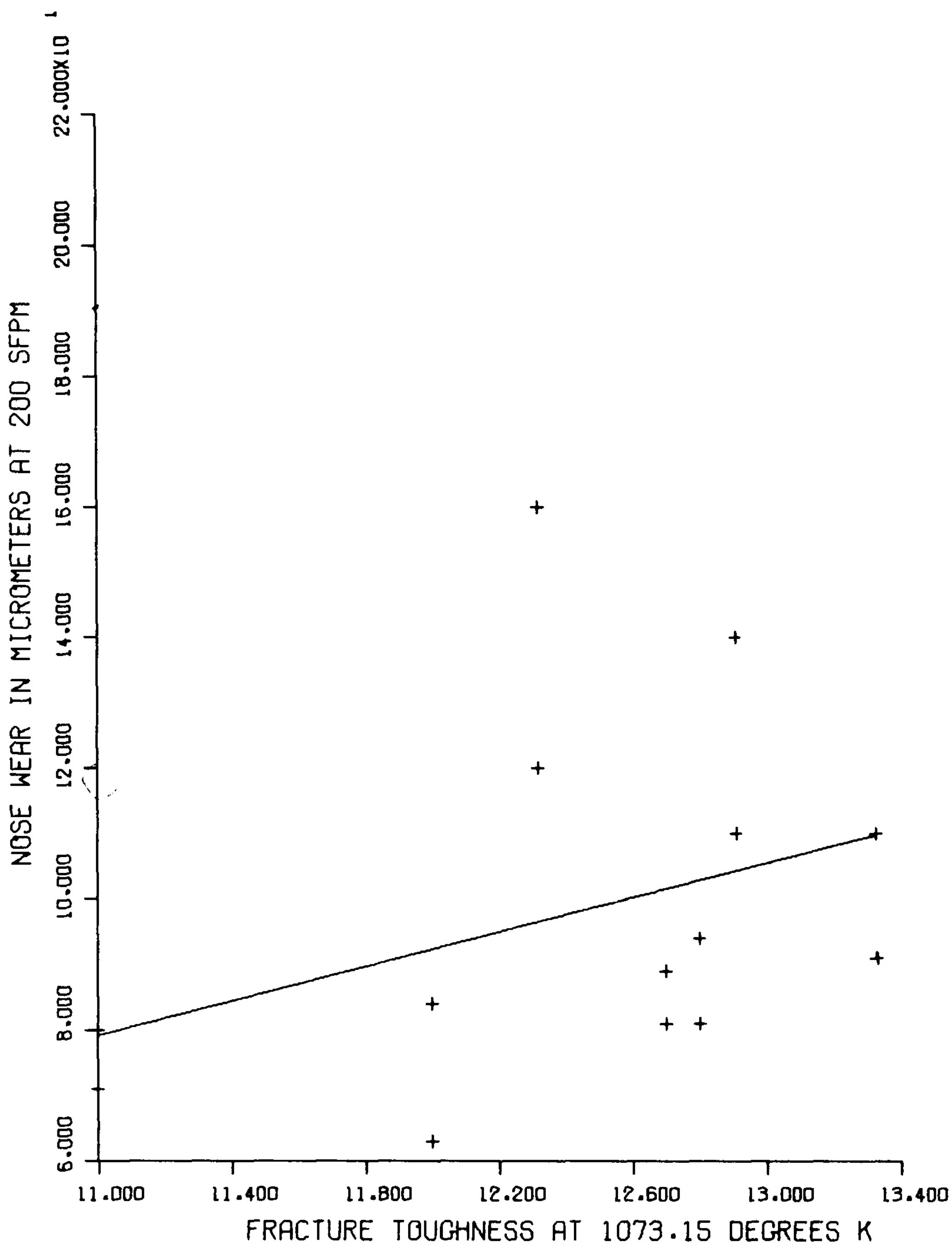
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 95



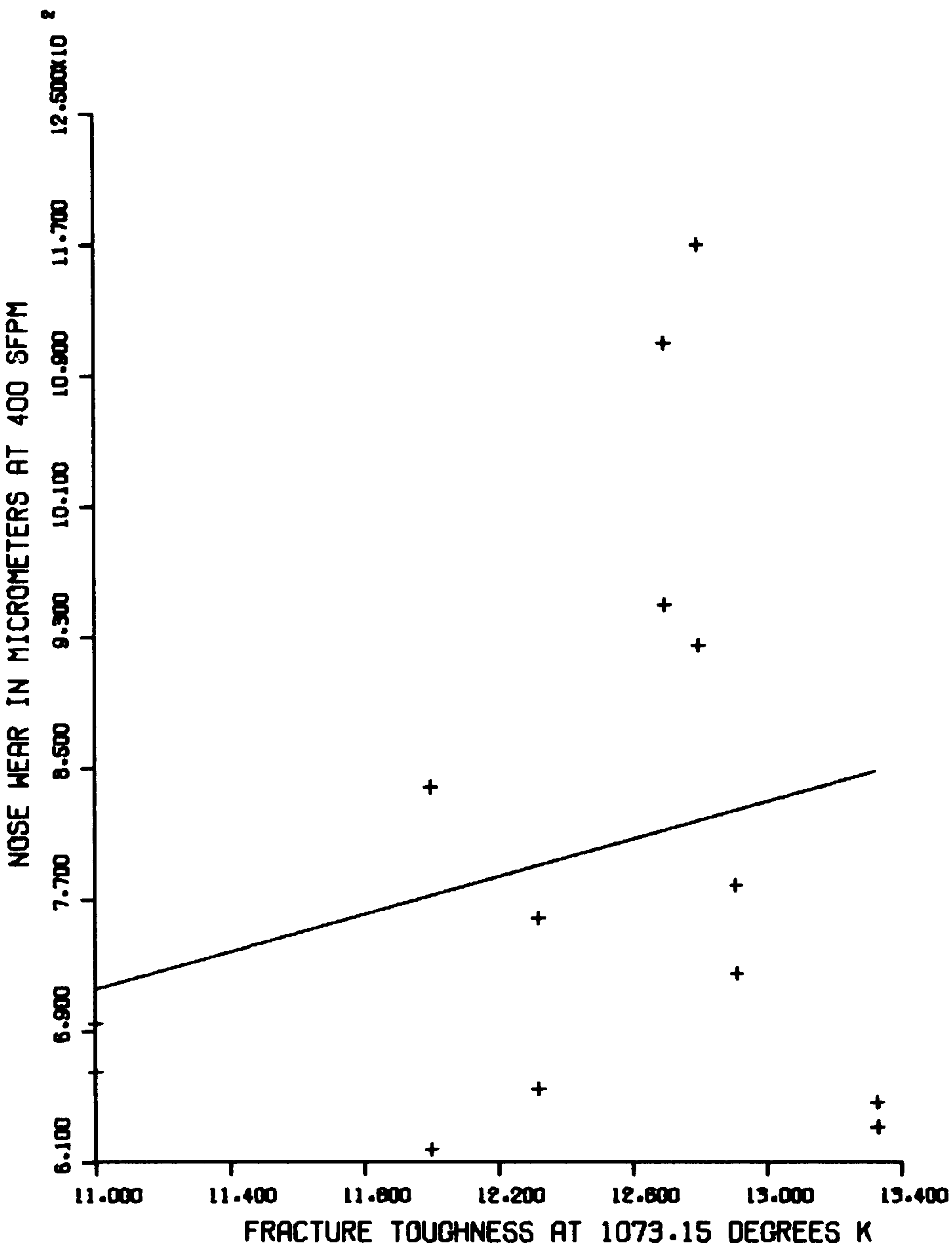
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 96



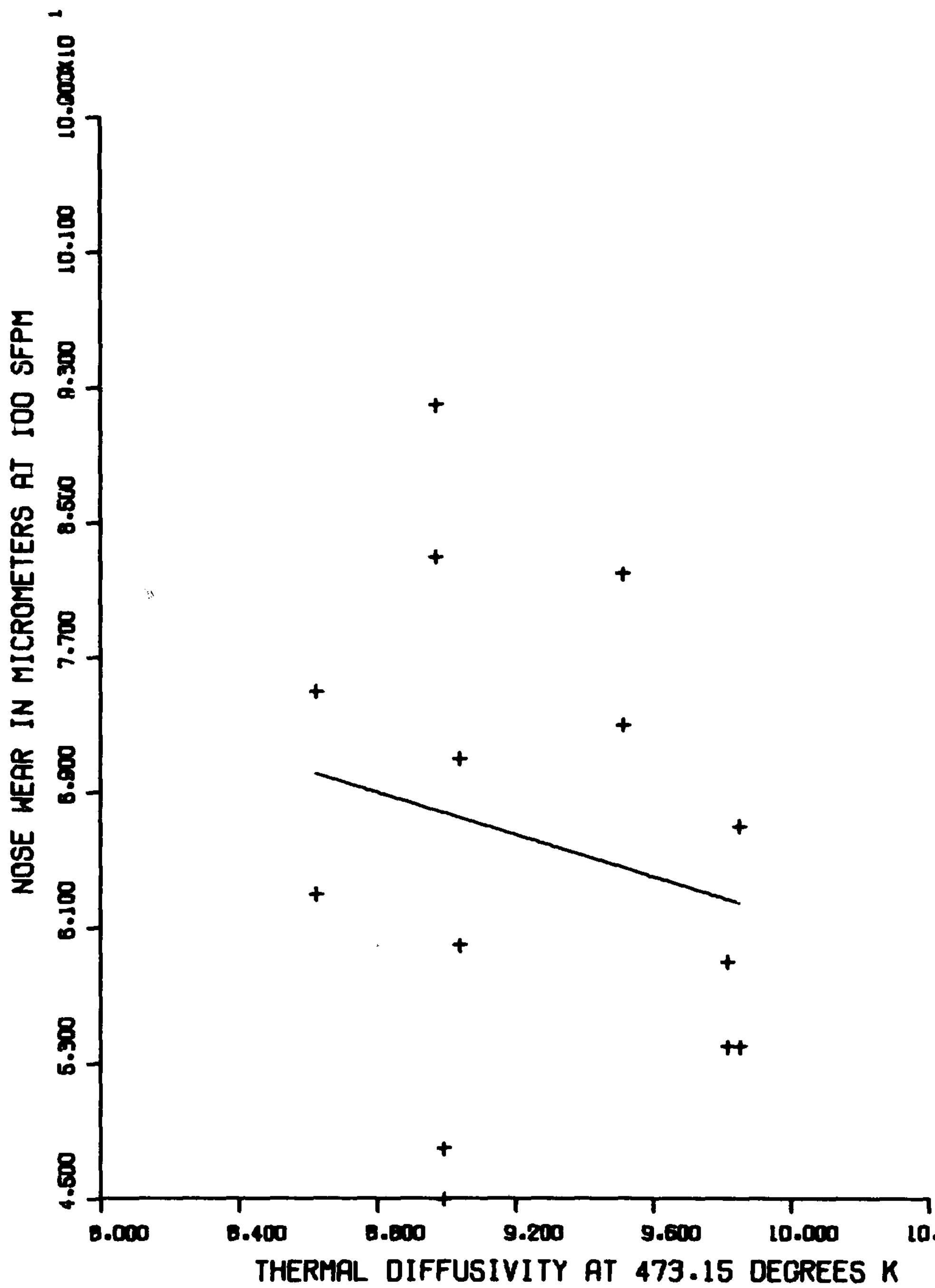
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 97



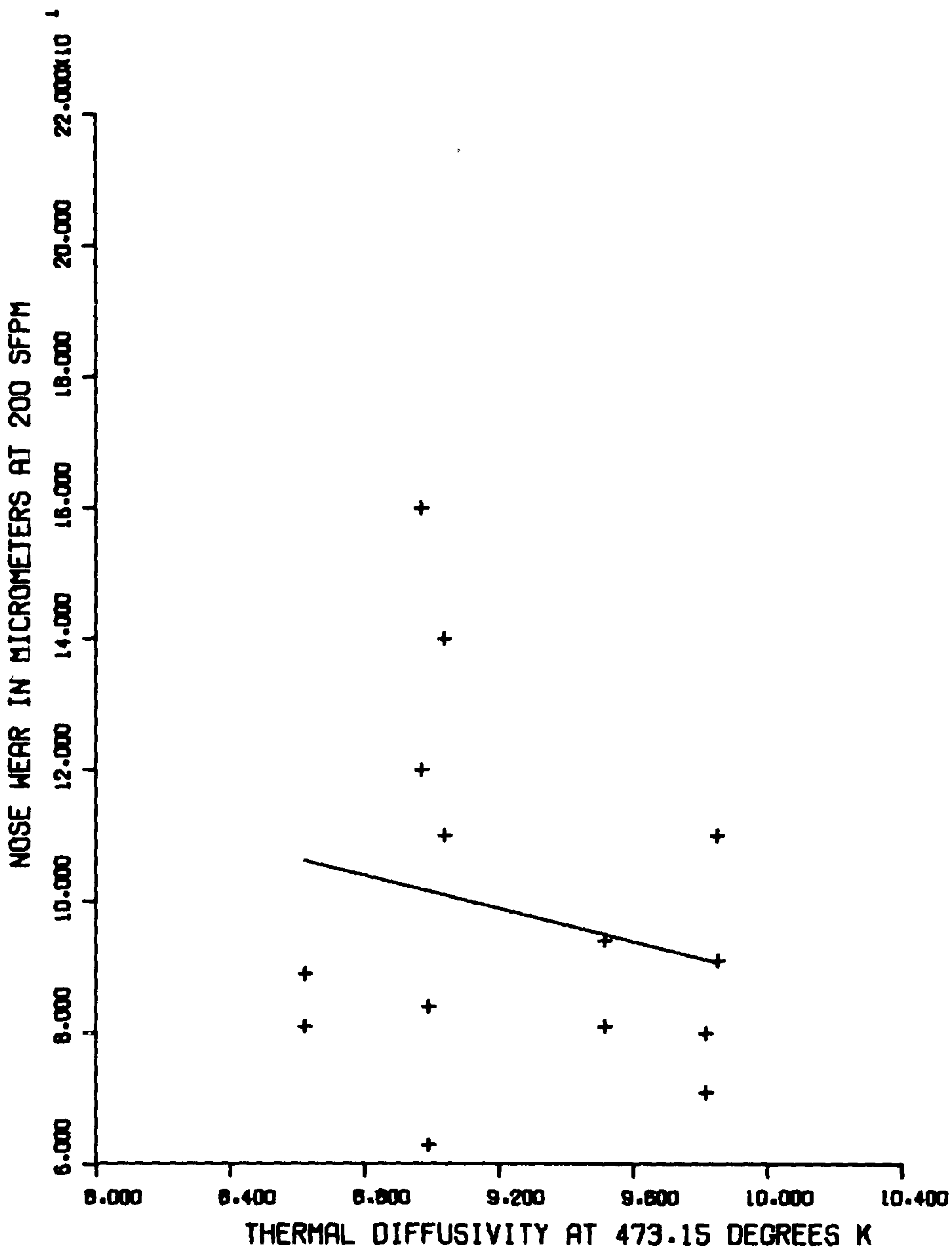
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 98



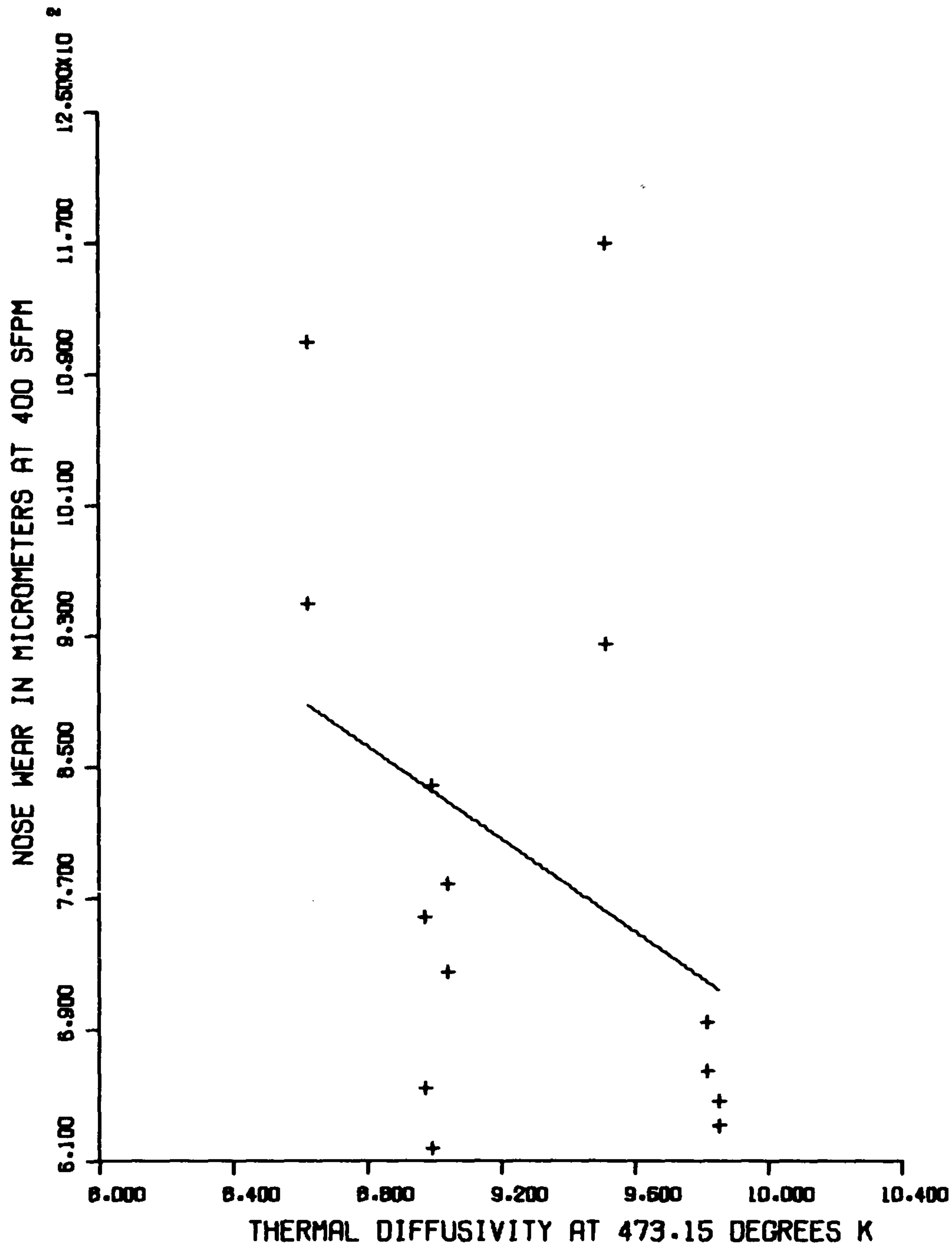
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 99



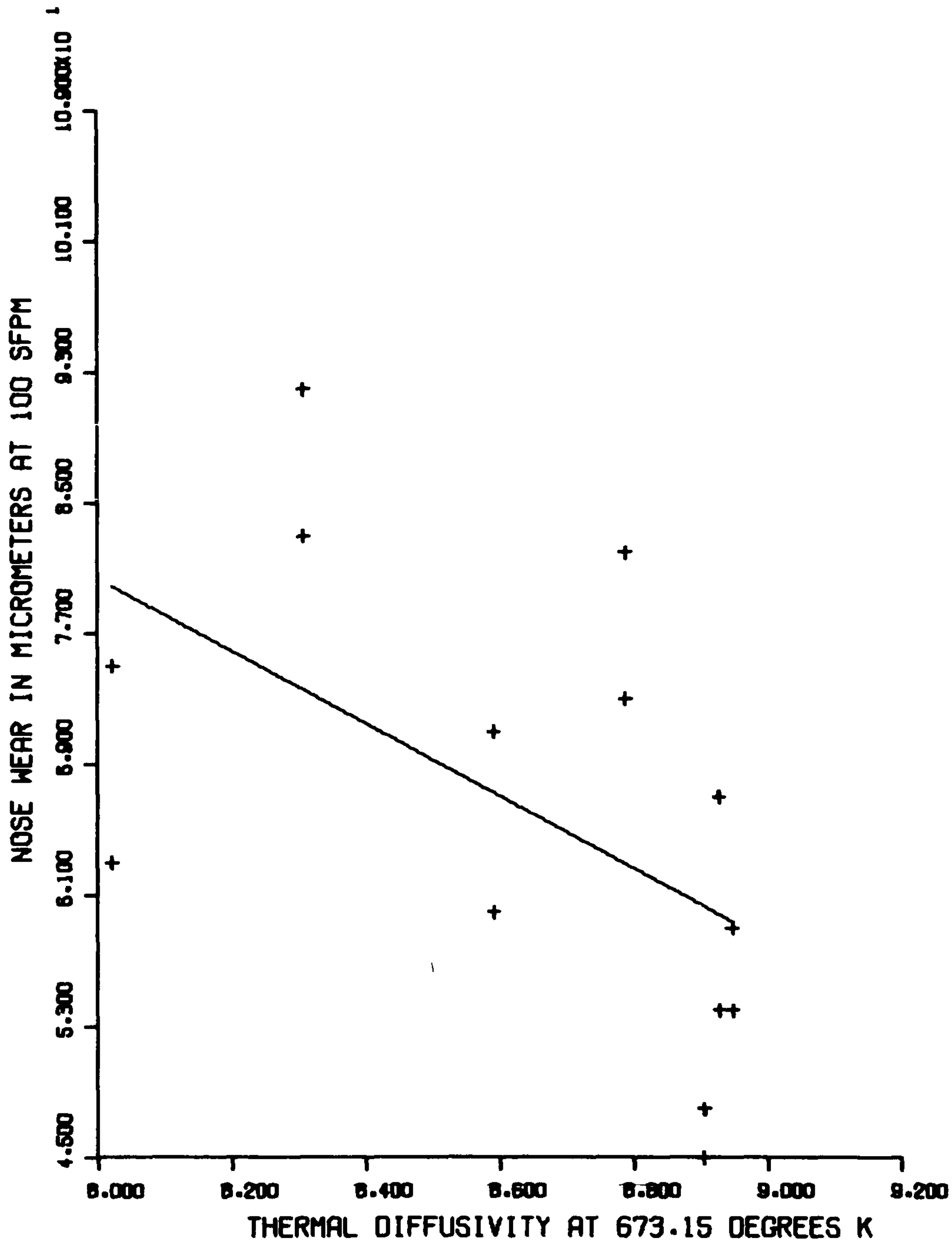
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 100



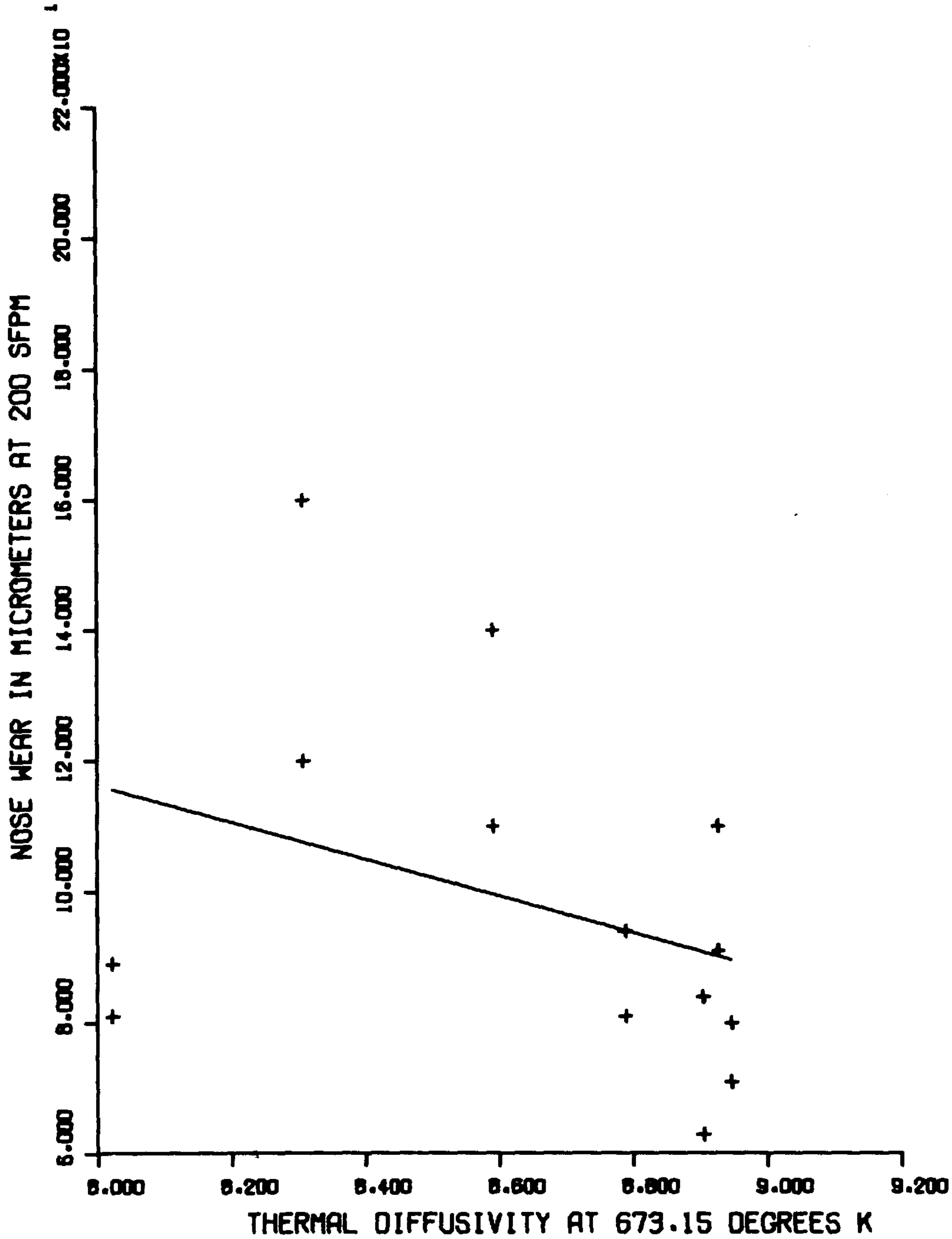
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 101



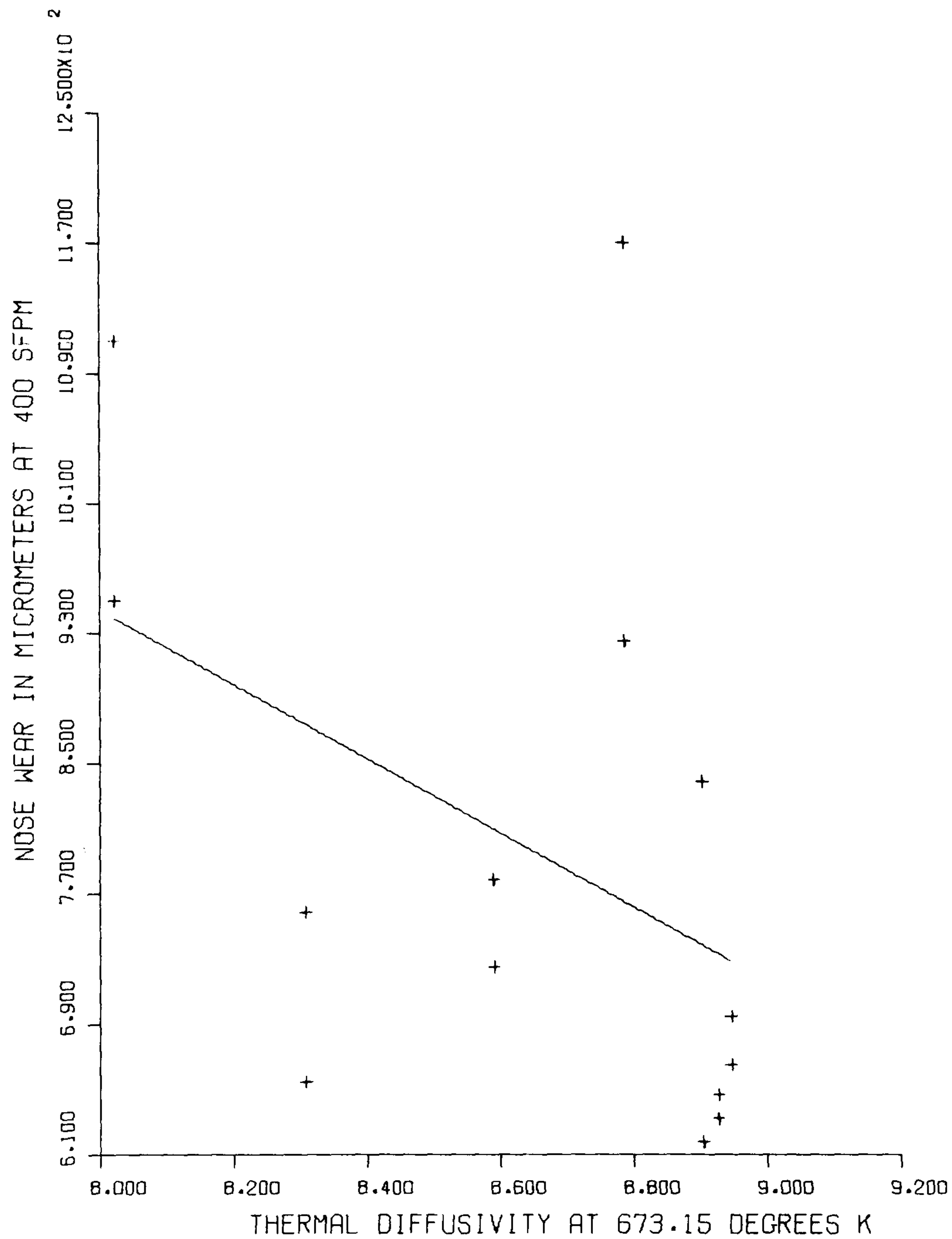
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 102



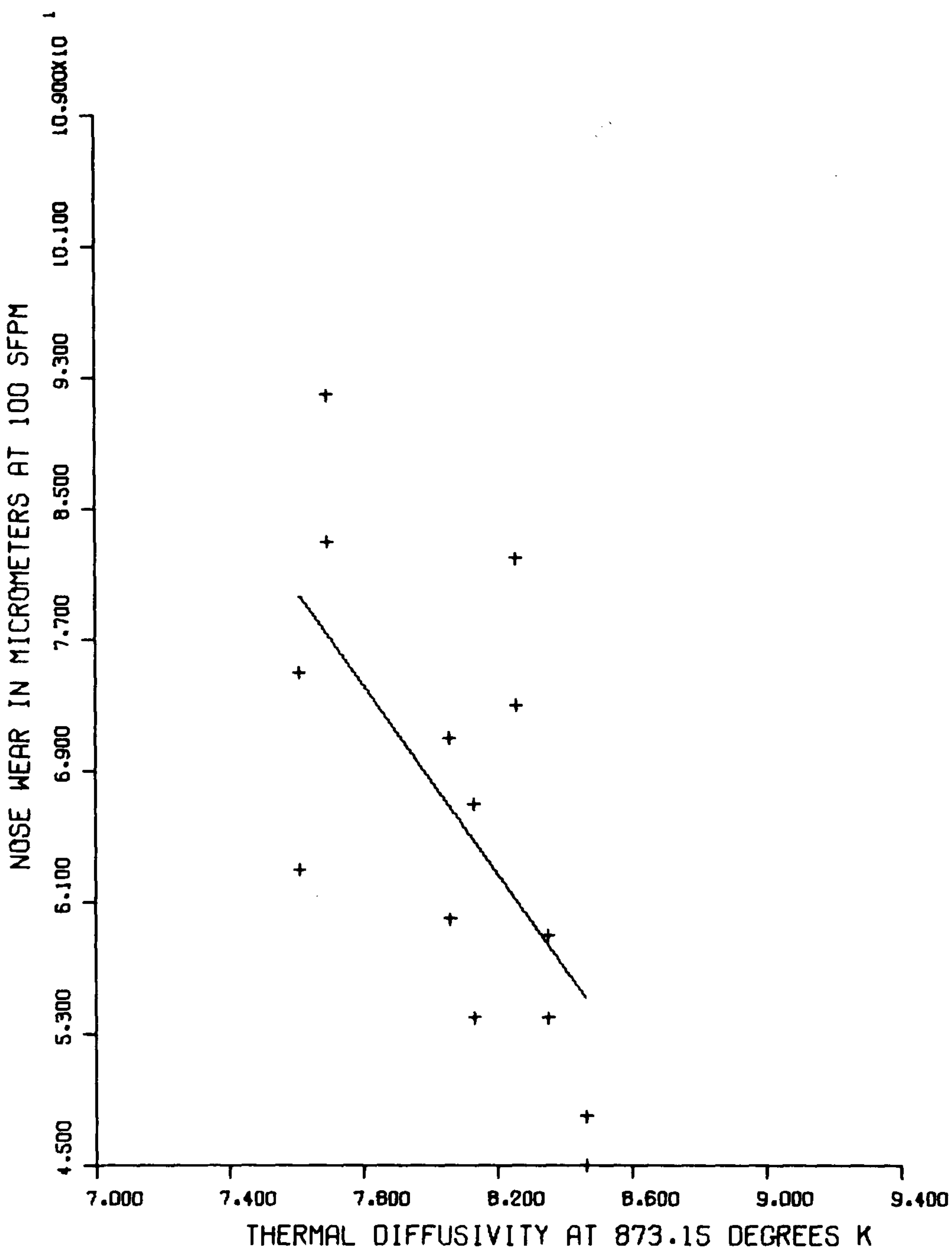
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 103



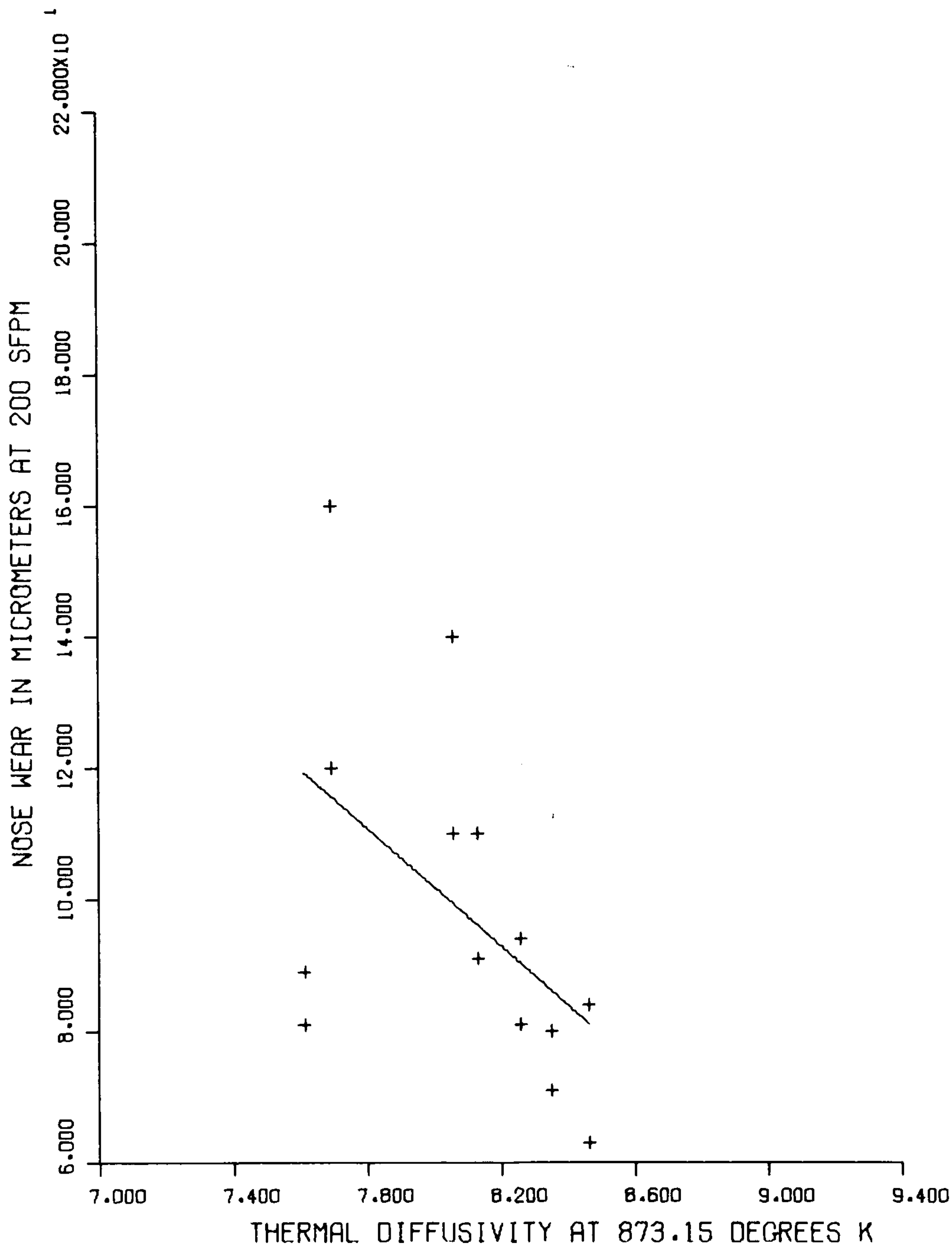
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 104



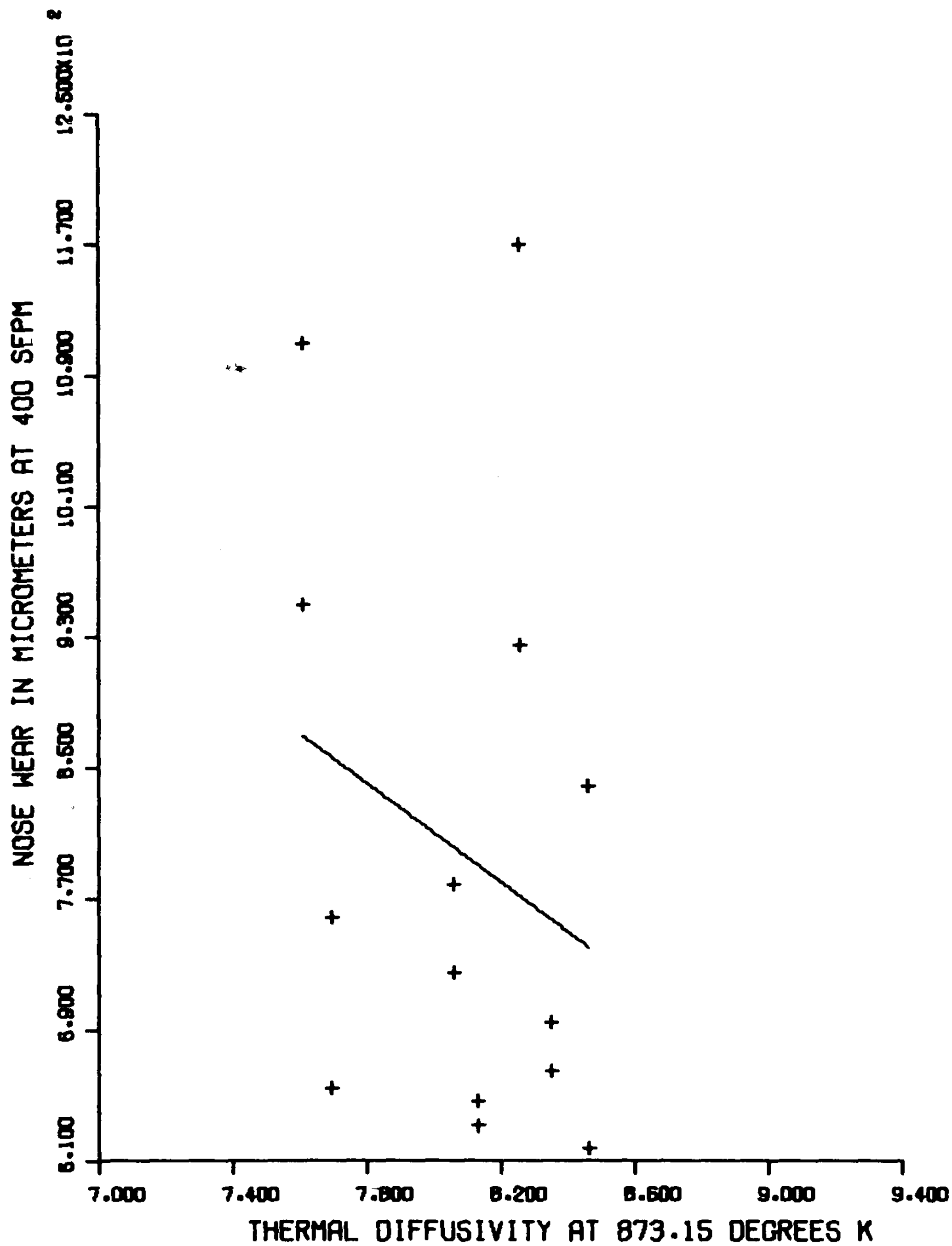
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 105



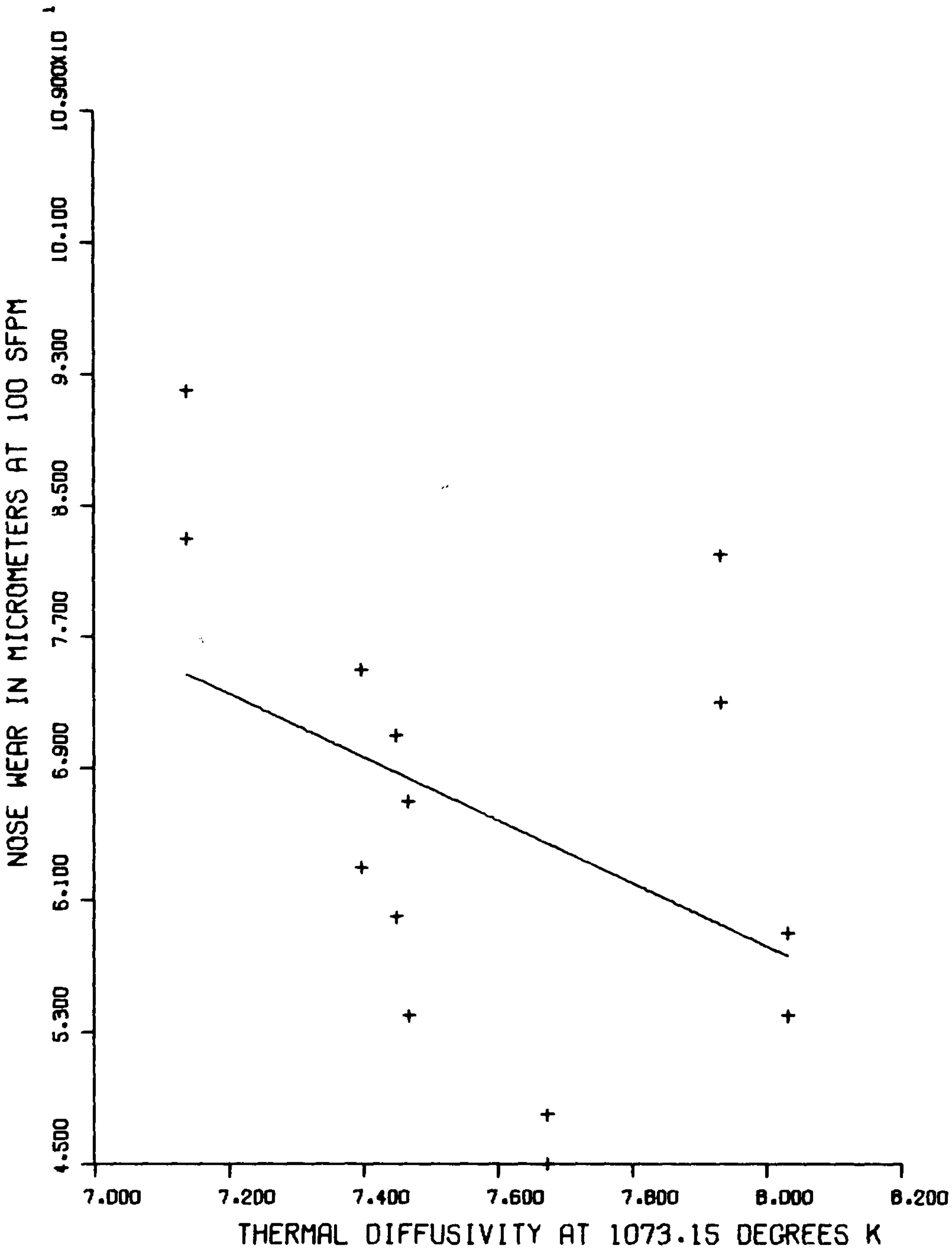
NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 106



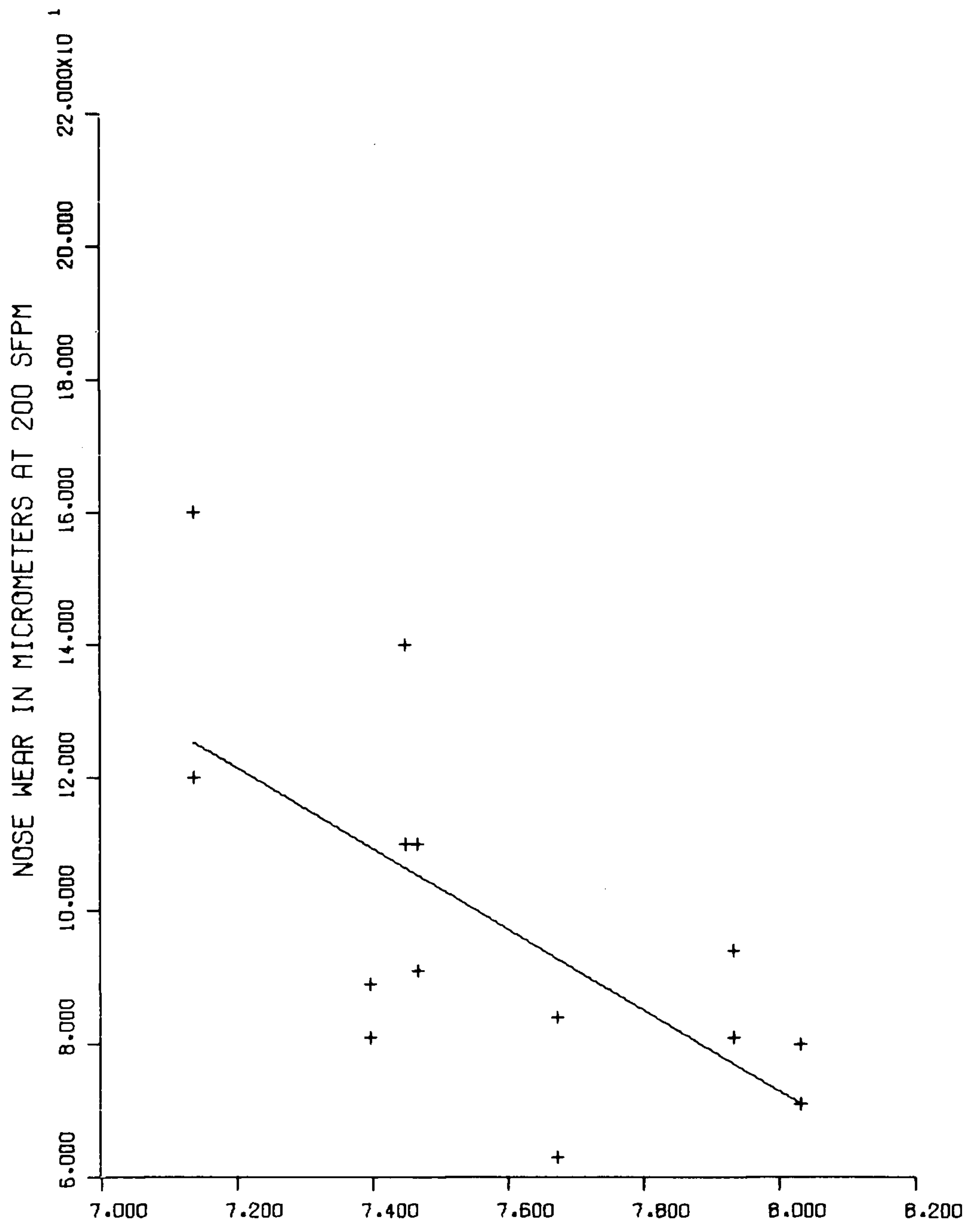
NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

FIGURE 107



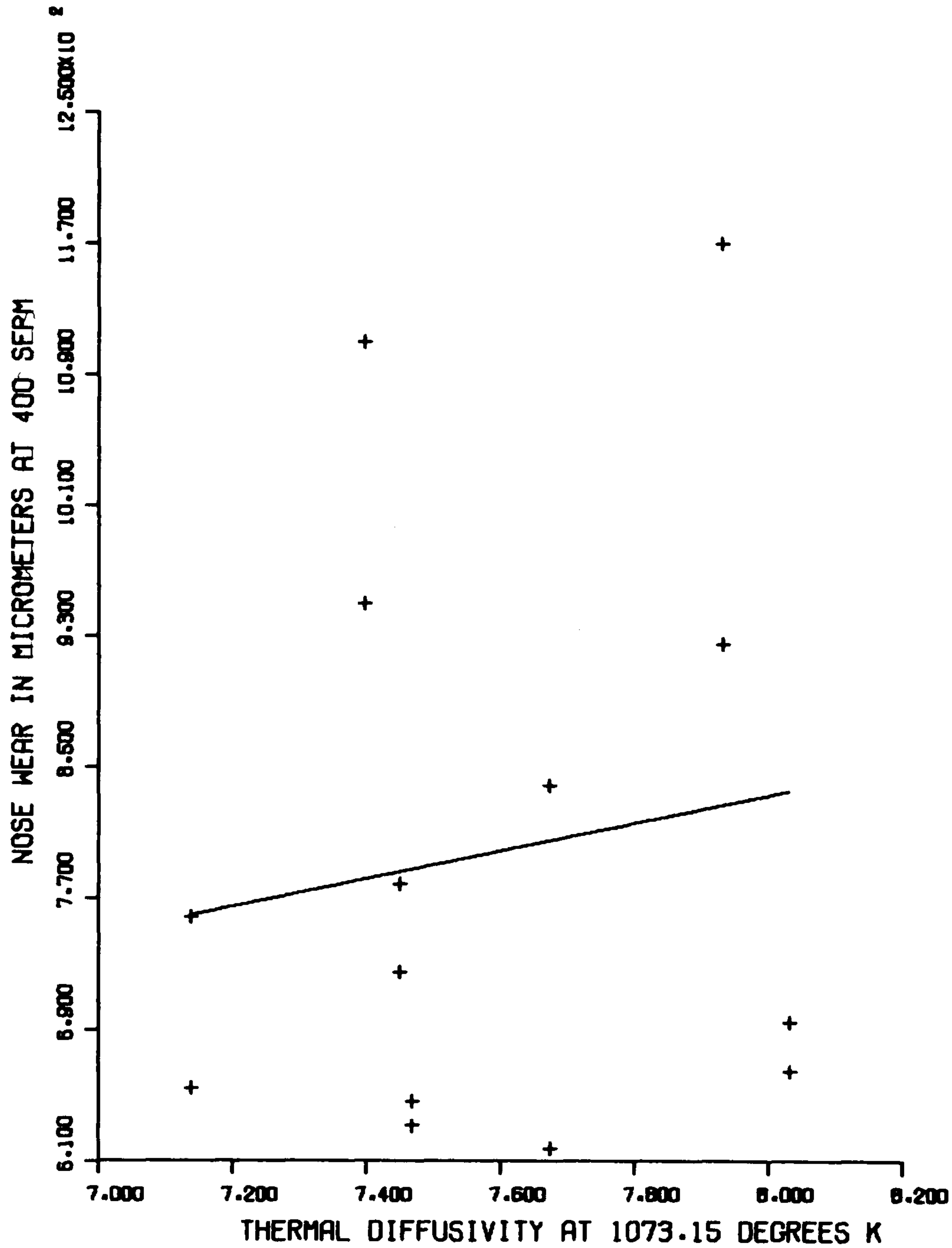
NOSE WEAR AT 100 SFPM VS. INDEP. PROPERTY

FIGURE 108



NOSE WEAR AT 200 SFPM VS. INDEP. PROPERTY

FIGURE 109



NOSE WEAR AT 400 SFPM VS. INDEP. PROPERTY

Many of the plots show that a decay type function seems to exist; note coercive force versus flank wear for all conditions. For others, a minimum, or maximum point for an independent property seems to be located on a concave downward, or a convex upward, parabolic type of relationship. In general, the distributions do not at all fit a straight line, and an exhaustive study of the individual relationships is beyond the scope of this work, so it suffices to note the lack of linear relationships displayed. It is not known whether the scatter plots shown are representative of the complete range of property values, and it is seen that some of the ranges of property measurements are much narrower than the available carbide grades would indicate.

Keeping the problems of regression analysis in mind, and also, being aware of the problems inherent with the data, it was felt that some method should be sought to provide reliable results from the regressions. In other words, producing regression results that were closely similar for all four data groups would be meaningful.

An attempt was then made to screen out those independent properties with high correlation with others, such as density, and to also throw out those properties which were measured at room temperature (298°K), and at 1073°K. These properties showed little success in predicting performance anyway, as shown by the initial stepwise regressions. Also, the tool never operates at these temperatures for the cutting conditions utilized.

The list of selected independent variables which are left,out of the original 17, is shown in Table XXXVI. The results of the stepwise regressions are shown for each of the four data groups in Tables XXXVII,XXXVIII, XXXIX, and XL. A summary listing of the results of the same regressions is provided in Table XLI.

Upon examination of Table XLI, we see much more uniform results for all four data groups, when compared to the results from before, where all seventeen variables were allowed to enter. The reader will note that only three property variables are shown for some conditions, this is due to the final, regular multiple linear regression results, i.e. three, or four variables might be used, depending upon which number produced the best overall regression statistics.

Now the average of the two replicates, and the combined data from replicates one and two, for all cutting conditions and both wear types, exactly match. Even the results for each individual replicate are much more similar than before. We have paid a price to get in; that being regression statistics which will be worse than before. But, it was felt that somewhat lower total amounts

TABLE XXXVI

SELECTED INDEPENDENT VARIABLES ALLOWED TO ENTER SECOND ROUND OF STEPWISE REGRESSIONS

1. Grain Size, μm.
2. Coercive Force, Oe.
3. Vickers Hardness at 673.15°K (400°C).
4. Abrasion Factor.
5. Fracture Toughness at 673.15°K (400°C), $MN/m^2 - m^{1/2}$.
4. Thermal Diffusivity at 473.15°K (200°C), mm^2/sec.
5. Thermal Diffusivity at 673.15°K (400°C), mm^2/sec.
6. Thermal Diffusivity at 873.15°K (600°C), mm^2/sec.

TABLE XXXVII

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR

(SELECTED INDEPENDENT VARIABLES - REPLICATE ONE)

Independent Property	Condition One		Condition Two		Condition Three	
	Flank	Nose	Flank	Nose	Flank	Nose
x_1 - Grain Size	↑(1)	↑(2)	NE	↑(3)	↑(3)	↑(1)
x_3 - Coercive Force	NE	↑(3)	NE	NE	↑(1)	↑(3)
x_7 - Vickers Hardness at 673.15°K	NE	↓(4)	↓(1)	NE	↓(2)	↓(4)
x_{10} - Abrasion Factor	↓(3)	NE	↑(4)	NE	NE	NE
x_{12} - Fracture Toughness at 673.15°K	↑(2)	NE	NE	↑(1)	NE	NE
x_{14} - Thermal Diffusivity at 473.15°K	NE	NE	↑(2)	NE	NE	NE
x_{15} - Thermal Diffusivity at 673.15°K	NE	NE	NE	NE	NE	NE
x_{16} - Thermal Diffusivity at 873.15°K	NE	↓(1)	↓(3)	↓(2)	NE	↓(2)

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

TABLE XXXVIII

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR
(SELECTED INDEPENDENT VARIABLES - REPLICATE TWO)

	Condition One		Condition Two		Condition Three	
Independent Property	Flank	Nose	Flank	Nose	Flank	Nose
x_1 - Grain Size	↑(1)	↑(3)	↑(3)	↑(4)	NE	NE
x_3 - Coercive Force	NE	NE	NE	NE	NE	NE
x_7 - Vickers Hardness at 673.15°K	NE	NE	↑(1)	NE	NE	↓(3)
x_{10} - Abrasion Factor	NE	↑(4)	NE	NE	NE	NE
x_{12} - Fracture Toughness at 673.15°K	↑(2)	NE	↑(2)	NE	↑(4)	↓(2)
x_{14} - Thermal Diffusivity at 473.15°K	NE	NE	↓(4)	↓(3)	↑(1)	↑(1)
x_{15} - Thermal Diffusivity at 673.15°K	↓(3)	↑(2)	NE	↑(2)	↓(3)	NE
x_{16} - Thermal Diffusivity at 873.15°K	NE	↓(1)	NE	↓(1)	↑(2)	↑(4)

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

TABLE XXXIX

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR
(SELECTED INDEPENDENT VARIABLES - AVERAGE OF REPLICATES)

Independent Property	Condition One Flank	Condition One Nose	Condition Two Flank	Condition Two Nose	Condition Three Flank	Condition Three Nose
x_1 - Grain Size	↑(1)	↑(2)	↑(3)	↑(3)	↑(2)	↑(2)
x_3 - Coercive Force	NE	NE	NE	NE	NE	↑(4)
x_7 - Vickers Hardness at 673.15°K	↓(4)	NE	↓(1)	NE	↓(1)	NE
x_{10} - Abrasion Factor	↓(3)	NE	NE	NE	↓(4)	NE
x_{12} - Fracture Toughness at 673.15°K	↑(2)	NE	↑(2)	↑(2)	NE	NE
x_{14} - Thermal Diffusivity at 473.15°K	NE	↓(4)	NE	NE	NE	NE
x_{15} - Thermal Diffusivity at 673.15°K	NE	↑(3)	NE	NE	NE	↓(1)
x_{16} - Thermal Diffusivity at 873.15°K	NE	↓(1)	↓(4)	↓(1)	↑(3)	↑(3)

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

TABLE XL

ROLES AND DIRECTIONS OF PROPERTY VALUES TO CAUSE INCREASING WEAR

(SELECTED INDEPENDENT VARIABLES - REPLICATES ONE AND TWO)

Independent Property	Condition One		Condition Two		Condition Three	
	Flank	Nose	Flank	Nose	Flank	Nose
x_1 - Grain Size	↑(1)	↑(2)	↑(3)	↑(3)	↑(2)	↑(2)
x_3 - Coercive Force	NE	NE	NE	NE	NE	NE
x_7 - Vickers Hardness at 673.15°K	↓(4)	NE	↓(1)	NE	↓(1)	NE
x_{10} - Abrasion Factor	↓(3)	NE	NE	NE	↓(4)	NE
x_{12} - Fracture Toughness at 673.15°K	↑(2)	NE	↑(2)	↑(2)	NE	NE
x_{14} - Thermal Diffusivity at 473.15°K	NE	NE	NE	NE	NE	NE
x_{15} - Thermal Diffusivity at 673.15°K	NE	↑(3)	NE	↑(3)	NE	↓(1)
x_{16} - Thermal Diffusivity at 873.15°K	NE	↓(1)	↓(4)	↓(1)	↑(3)	↑(3)

Type of Role - (1) Primary, (2) Secondary, (3) Tertiary, (4) Quaternary,
NE - Never Entered.

TABLE XLI

COMPARISON OF RESULTS FOR DIFFERENT DATA GROUPS(1)

(SELECTED INDEPENDENT VARIABLES)

CONDITION ONE

	Replicate One		Replicate Two		Average of Replicates		Replicate One and Two	
Role	Flank	Nose	Flank	Nose	Flank	Nose	Flank	Nose
Primary	$\uparrow x_1$	$\downarrow x_{16}$	$\uparrow x_1$	$\downarrow x_{16}$	$\uparrow x_1$	$\downarrow x_{16}$	$\uparrow x_1$	$\downarrow x_{16}$
Secondary	$\uparrow x_{12}$	$\uparrow x_1$	$\uparrow x_{12}$	$\uparrow x_{15}$	$\uparrow x_{12}$	$\uparrow x_1$	$\uparrow x_{12}$	$\uparrow x_1$
Tertiary	$\downarrow x_{10}$	$\uparrow x_3$	$\downarrow x_{15}$	$\uparrow x_1$	$\downarrow x_{10}$	$\uparrow x_{15}$	$\downarrow x_{10}$	$\uparrow x_{15}$
Quaternary		$\downarrow x_7$		$\uparrow x_{10}$	$\downarrow x_7$	$\downarrow x_{14}$	$\downarrow x_7$	

CONDITION TWO

	Replicate One		Replicate Two		Average of Replicates		Replicate One and Two	
Role	Flank	Nose	Flank	Nose	Flank	Nose	Flank	Nose
Primary	$\downarrow x_7$	$\uparrow x_{12}$	$\uparrow x_7$	$\downarrow x_{16}$	$\downarrow x_7$	$\downarrow x_{16}$	$\downarrow x_7$	$\downarrow x_{16}$
Secondary	$\uparrow x_{14}$	$\downarrow x_{16}$	$\uparrow x_{12}$	$\uparrow x_{15}$	$\uparrow x_{12}$	$\uparrow x_{12}$	$\uparrow x_{12}$	$\uparrow x_{12}$
Tertiary	$\downarrow x_{16}$	$\uparrow x_1$	$\uparrow x_1$	$\downarrow x_{14}$	$\uparrow x_1$	$\uparrow x_1$	$\uparrow x_1$	$\uparrow x_1$
Quaternary	$\uparrow x_{10}$		$\downarrow x_{14}$	$\uparrow x_1$	$\downarrow x_{16}$		$\downarrow x_{16}$	$\uparrow x_{15}$

CONDITION THREE

	Replicate One		Replicate Two		Average of Replicates		Replicate One and Two	
Role	Flank	Nose	Flank	Nose	Flank	Nose	Flank	Nose
Primary	$\uparrow x_3$	$\uparrow x_1$	$\uparrow x_7$	$\uparrow x_{14}$	$\downarrow x_7$	$\downarrow x_{15}$	$\downarrow x_7$	$\downarrow x_{15}$
Secondary	$\downarrow x_7$	$\downarrow x_{16}$	$\uparrow x_{16}$	$\downarrow x_{12}$	$\uparrow x_1$	$\uparrow x_1$	$\uparrow x_1$	$\uparrow x_1$
Tertiary	$\uparrow x_1$	$\uparrow x_3$	$\downarrow x_{15}$	$\downarrow x_7$	$\uparrow x_{16}$	$\uparrow x_{16}$	$\uparrow x_{16}$	$\uparrow x_{16}$
Quaternary		$\downarrow x_7$	$\uparrow x_{12}$	$\uparrow x_{16}$	$\downarrow x_{10}$	$\uparrow x_{13}$	$\downarrow x_{10}$	

(1) The arrows show the direction of the property to cause increasing wear.

of variance explained (R^2), lower F-statistics, etc. could be sacrificed for reliable predicting equations. Since the four data groups resulted in very similar results, and since it is felt that it best represents the data obtained in performance evaluation, the group comprised of replicates one and two combined were used to calculate final regression equations by utilizing the regular multiple linear regression task of LEAPS[21].

The final regressions, and their significant outputs, are presented in Tables XLII,XLIII,XLIV,XLV,XLVI, and XLVII. The output includes the equation form, the variables and their respective coefficients listed in order of importance, the actual versus predicted values for the wear, the multiple correlation (r), the standard error of the estimate, and the F-statistics for each of the six dependent variables. Refer to Table XXIX for the identification of the coded variables.

Even with the reduced number of independent variables available to the regression to reduce the largest amount of variance with the first three, or four variables entered, all of the regressions had correlations which were significant at the 90% level of confidence. In fact, four were significant at the 99% level; these four were the only ones significant at the 95% level. Apparently,the sacrifice made to gain some reliability, did not hurt the

TABLE XLII

FLANK WEAR - CONDITION ONE

SELECTED INDEPENDENT VARIABLES - REPLICATES ONE AND TWO

$$Y_1 = b_0 + a_1 x_1 + a_{12} x_{12} + a_{10} x_{10} + a_7 x_7$$

b, a	COEFFICIENT	STANDARD ERROR
b_0	-1.2557×10^{2}	--------------
a_1	8.5852×10^{1}	1.5503×10^{1}
a_{12}	7.6213×10^{0}	1.9687×10^{0}
a_{10}	-2.0916×10^{0}	1.1257×10^{0}
a_7	-5.9894×10^{-2}	4.1937×10^{-2}

ALLOY CODES	FLANK WEAR, μm ACTUAL	PREDICTED
A1, A2	25., 27.	24.1
B1, B2	31., 29.	37.1
C1, C2	42., 46.	44.5
D1, D2	62., 51.	51.6
E1, E2	29., 26.	26.6
F1, F2	35., 29.	28.8
G1, G2	37., 34.	38.8

Multiple Correlation = .8951

Standard Error of Estimate = 5.7879×10^{0}

F statistic of regression = 9.07

F - critical = 2.69

$\nu_1 = 4$, $\nu_2 = 9$, $\alpha = 0.10$

TABLE XLIII

NOSE WEAR - CONDITION ONE

SELECTED INDEPENDENT VARIABLES - REPLICATES ONE AND TWO

$$Y_2 = b_0 + a_{16}x_{16} + a_1x_1 + a_{15}x_{15}$$

b, a	COEFFICIENT	STANDARD ERROR
b_0	2.5436×10^2	--------------
a_{16}	-8.7274×10^1	2.1560×10^1
a_1	5.6056×10^1	1.4295×10^1
a_{15}	4.8827×10^1	1.8878×10^1

ALLOY CODES	NOSE WEAR, μm ACTUAL	PREDICTED
A1, A2	54., 67.	60.6
B1, B2	83., 92.	85.9
C1, C2	60., 71.	60.1
D1, D2	82., 73.	73.5
E1, E2	48., 45.	45.7
F1, F2	75., 63.	72.9
G1, G2	54., 59.	64.3

Multiple Correlation = .8810

Standard Error of Estimate = 7.5152×10^0

F statistic of regression = 11.56

F - critical = 2.73

$\nu_1 = 3$, $\nu_2 = 10$, $\alpha = 0.10$

TABLE XLIV

FLANK WEAR - CONDITION TWO

SELECTED INDEPENDENT VARIABLES - REPLICATES ONE AND TWO

$$Y_3 = b_0 + a_7 x_7 + a_{12} x_{12} + a_1 x_1 + a_{16} x_{16}$$

b, a	COEFFICIENT	STANDARD ERROR
b_0	1.5695×10^2	--------------
a_7	-1.0972×10^{-1}	6.6560×10^{-2}
a_{12}	1.1063×10^1	2.4241×10^0
a_1	6.1842×10^1	1.6974×10^1
a_{16}	-3.3014×10^1	9.4926×10^0

ALLOY CODES	FLANK WEAR, μm ACTUAL	PREDICTED
A1, A2	54., 59.	58.0
B1, B2	82., 83.	76.1
C1, C2	96., 97.	96.2
D1, D2	63., 70.	68.8
E1, E2	45., 63.	49.9
F1, F2	74., 64.	73.5
G1, G2	61., 51.	58.6

Multiple Correlation = .9233

Standard Error of Estimate = 7.3438×10^0

F statistic of regression = 13.00

F - critical = 2.69

$\nu_1 = 4, \nu_2 = 9, \alpha = 0.10$

TABLE XLV

NOSE WEAR - CONDITION TWO

SELECTED INDEPENDENT VARIABLES - REPLICATES ONE AND TWO

$$Y_4 = b_0 + a_{16}x_{16} + a_{12}x_{12} + a_1x_1 + a_{15}x_{15}$$

b, a	COEFFICIENT	STANDARD ERROR
b_0	2.3481×10^2	--------------
a_{16}	-1.2415×10^2	5.7400×10^1
a_{12}	1.3889×10^1	6.0991×10^0
a_1	7.1281×10^1	4.6270×10^1
a_{15}	6.0143×10^1	5.1083×10^1

ALLOY CODES	NOSE WEAR, μm ACTUAL	PREDICTED
A1, A2	91., 110.	105.8
B1, B2	121., 156.	118.6
C1, C2	141., 109.	123.5
D1, D2	94., 81.	94.2
E1, E2	63., 84.	59.4
F1, F2	89., 81.	98.7
G1, G2	80., 71.	85.3

Multiple Correlation = .7806

Standard Error of Estimate = 1.9989×10^1

F statistic of regression = 3.51

F - critical = 2.69

$\nu_1 = 4$, $\nu_2 = 9$, $\alpha = 0.10$

TABLE XLVI

FLANK WEAR - CONDITION THREE

SELECTED INDEPENDENT VARIABLES - REPLICATES ONE AND TWO

$$Y_5 = b_0 + a_7 x_7 + a_1 x_1 + a_{16} x_{16} + a_{10} x_{10}$$

b, a	COEFFICIENT	STANDARD ERROR
b_0	9.9983×10^2	--------------
a_7	-1.8840×10^0	4.1182×10^{-1}
a_1	1.5685×10^2	4.1775×10^1
a_{16}	1.5911×10^2	6.8564×10^1
a_{10}	-1.9901×10^1	1.0011×10^1

ALLOY CODES	FLANK WEAR, μm ACTUAL	PREDICTED
A1, A2	174., 177.	174.3
B1, B2	248., 212.	227.7
C1, C2	285., 316.	301.1
D1, D2	282., 245.	258.9
E1, E2	250., 258.	249.1
F1, F2	304., 291.	299.5
G1, G2	230., 203.	227.0

Multiple Correlation = .9488

Standard Error of Estimate = 1.7107×10^1

F statistic of regression = 20.31

F - critical = 2.69

$\nu_1 = 4, \nu_2 = 9, \alpha = 0.10$

TABLE XLVII

NOSE WEAR - CONDITION THREE

SELECTED INDEPENDENT VARIABLES - REPLICATES ONE AND TWO

$$Y_6 = b_0 + a_{15} x_{15} + a_1 x_1 + a_{16} x_{16}$$

b, a	COEFFICIENT	STANDARD ERROR
b_0	1.5172×10^3	--------------
a_{15}	-4.9801×10^2	3.0345×10^2
a_1	3.7827×10^2	2.8845×10^2
a_{16}	3.6675×10^2	4.1233×10^2

ALLOY CODES	NOSE WEAR, μm ACTUAL	PREDICTED
A1, A2	632., 647.	595.1
B1, B2	760., 655.	860.4
C1, C2	725., 779.	799.9
D1, D2	1170., 925.	918.8
E1, E2	619., 839.	667.5
F1, F2	950., 1109.	931.1
G1, G2	666., 696.	813.0

Multiple Correlation = .6763

Standard Error of Estimate = 1.4985×10^2

F statistic of regression = 2.81

F - critical = 2.73

$\nu_1 = 3,\ \nu_2 = 10,\ \alpha = 0.10$

ability of the equations to accurately predict performance very much.

The two worst results were for the nose wear in conditions two and three. Since both of these conditions caused the tool to be run at a fairly high rate of speed, and therefore, higher ambient temperatures, it may be possible that the assumption of lying on the straight, gradual wear part of the total wear curve after nine minutes of cutting was invalid.

A promising result was that thermal diffusivity entered in many cases, especially for nose wear in all three conditions where it played primary roles. Tertiary and quaternary roles were also exhibited for the same cases and nose wear.

For the most part, considering only the results of the data group consisting of replicate one combined with replicate two, the independent properties had a consistent effect on wear whenever they entered a regression. Also, they behaved in a manner that has been qualitatively observed, or that might intuitively be expected. It must be remembered that collinearity was still a problem, and most signs which are in disagreement with the majority, were also opposite to their partial correlations with the dependent variable.

A general summary of the roles of the various independent variables is shown below.

<u>Property and Type of Role</u>

A. Primary

1. (x_1) Grain Size
2. (x_7) Vickers Hardness at 673°K
3. (x_{15}) Thermal Diffusivity at 673°K
4. (x_{16}) Thermal Diffusivity at 873°K

B. Secondary

1. (x_1) Grain Size
2. (x_{12}) Fracture Toughness at 673°K

C. Tertiary

1. (x_1) Grain Size
2. (x_{10}) Abrasion Factor
3. (x_{15}) Thermal Diffusivity at 673°K
4. (x_{16}) Thermal Diffusivity at 873°K

Other properties not listed had minor roles.

An attempt was made during this study to widen the matrix examined by Scheithauer, but, only a small part of the rather large matrix was examined. There are many variables within the tool material, the machining conditions, and the workpiece properties which remain to be quantitatively evaluated in order to exactly define performance for all cutting situations. This study appears to indicate that many more observations are needed, along with more independent variables besides tool properties, to enable the characterization of each independent property versus the dependent variable, and then the total characterization of properties and performance.

CONCLUSIONS

The conclusions must necessarily be broken down into three sections; conclusions pertaining to the initial stepwise regressions run with all seventeen independent variables, conclusions pertaining to the final reduced variable matrix and regression results, and general conclusions.

A. Conclusions Pertaining to the Initial Stepwise Regressions with all Seventeen Independent Variables

(1.) A good correlation between tool properties and tool performance was demonstrated for all six dependent variables, no matter which of the four data groups was utilized.

(2.) Many of the properties typically measured on tungsten carbides never entered, or only played minor roles, in the regressions for all six dependent variables, no matter which of the four data groups was utilized.

(3.) Of the properties that played primary or secondary roles in the stepwise regressions for all six dependent variables, and for any of the four data groups used, over half were elevated temperature properties.

(4.) Different properties played different roles depending on the cutting condition and the type of wear. This was not surprising since different mechanisms are operative for different conditions of cut.

(5.) Different properties played different roles depending upon which of the four data groups was used. This was disturbing since the data groups were all constructed from replicates made under the same conditions. It must therefore be inferred that different regression equations can be resulted even for the same exact conditions, depending upon the particular replication of data used in defining the equation.

(6.) It seems that there is a fine line of difference between some of the variables' explanatory abilities. This was indicated by the regressions when different equations were resulted which were almost equally capable in predicting performance for any one condition.

(7.) Collinearity, resulting from high correlations between several of the independent variables, sometimes caused the coefficient of an independent variable to have the opposite sign from that variable's partial correlation with the dependent variable, thus, indicating the opposite relationship between two variables from what would logically be expected.

(8.) Since similar, and therefore, reliable results were not produced by the regressions for all four data groups, the validity of any one of the regressions is questioned as far as their ability to produce a general, yet accurate, predicting equation with which to define performance.

B. Conclusions Pertaining to the Final Reduced Variable Matrix and Regression Results

(1.) Again, different properties played different roles depending upon the cutting situation and the type of wear. Different mechanisms are operative for different cutting conditions.

(2.) Collinearity was not as predominant with the new reduced variables matrix, by design. Hence, discrepencies between the signs of the coefficients and the partial correlations with the dependent variables were not as prevalent.

(3.) Significant increases in equation generality, and hence, reliability, were made by using the reduced matrix of independent properties. The total variance explained by the regression was obviously reduced, but, the gains in reliability were substantial, with minimal loss of predicting accuracy.

(4.) Different properties now played more similar roles for each of the four data groups, and equal conditions. This was comforting because the data groups were constructed from two replicates made under the same conditions. Very similar regression equations were produced for the same conditions, even when quantitatively different replication data was used.

(5.) Since similar, and more generally reliable results were produced for the four data groups, the regression equations can be said to be more flexible and valid, when compared with the results produced from the initial stepwise regressions using all seventeen independent variables.

C. General Conclusions

(1.) Thermal diffusivity is an important explanatory variable in determining performance, especially for nose wear at higher operating speeds.

(2.) The relationships between most of the independent properties and wear are far from linear, assuming the scatter plots shown are representative of the total distribution. Thus, the use of multiple linear regression is limited in its abilities to accurately represent the true relationship of any number of independent variables to the dependent variable, wear, used in the analyses.

RECOMMENDATIONS FOR FUTURE WORK

1. The first step should be to collect many more observations, i.e. representative tool alloys, which will accurately represent the existing distribution of properties versus performance for each of the independent variables.

2. Individual curves should be developed to more accurately describe the true nature of the relationship between each independent versus dependent variable.

3. Some method of reducing the correlation between the independent properties should be sought, thus, reducing collinearity problems in regression.

4. A continuing search should be conducted for other tool properties, or other process variables, which could lead to equations better able to predict performance of tungsten carbide cutting tools.

5. Once the individual relationships between each independent property versus the dependent variables is defined, an attempt should be made at correlating properties with performance with some method of multiple curvilinear regression. Though no method, as such, exists to do this, there are ways to attempt multiple curvilinear regression by adaption of present regression techniques.

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APPENDIX

A

TABLE I - A

RAW THERMAL DIFFUSIVITY DATA - ALLOY A

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
1.	1084.15 (811)	7.423×10^{-6}
2.	" "	" "
3.	1077.15 (804)	7.217 "
4.	1056.15 (783)	7.423 "
5.	1055.15 (782)	7.217 "
6.	" "	7.423 "
7.	1014.15 (741)	7.873 "
8.	1013.15 (740)	" "
9.	1012.15 (739)	8.119 "
10.	969.15 (696)	7.641 "
11.	967.15 (694)	8.119 "
12.	966.15 (693)	7.873 "
13.	924.15 (651)	8.119 "
14.	919.15 (646)	" "
15.	918.15 (645)	" "
16.	882.15 (609)	" "
17.	881.15 (608)	" "
18.	879.15 (606)	" "
19.	842.15 (569)	" "
20.	841.15 (568)	" "
21.	839.15 (566)	" "
22.	796.15 (523)	" "
23.	794.15 (521)	" "
24.	793.15 (520)	" "
25.	750.15 (477)	8.381 "
26.	749.15 (476)	8.660 "
27.	747.15 (474)	8.119 "
28.	698.15 (425)	8.660 "
29.	697.15 (424)	8.959 "
30.	695.15 (422)	9.279 "
31.	653.15 (380)	" "
32.	652.15 (379)	" "
33.	651.15 (378)	" "
34.	605.15 (332)	" "
35.	604.15 (331)	9.622 "

TABLE I - A (continued)

RAW THERMAL DIFFUSIVITY DATA - ALLOY A

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
36.	602.15 (329)	9.279×10^{-6}
37.	553.15 (280)	9.622 "
38.	551.15 (278)	" "
39.	" "	8.959 "
40.	521.15 (248)	9.992 "
41.	520.15 (247)	9.279 "
42.	" "	" "

TABLE II - A

RAW THERMAL DIFFUSIVITY DATA - ALLOY B

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
1.	1069.15 (796)	8.660×10^{-6}
2.	" "	7.217 "
3.	1067.15 (794)	7.873 "
4.	1057.15 (784)	6.495 "
5.	" "	7.022 "
6.	" "	7.217 "
7.	1014.15 (741)	7.022 "
8.	1011.15 (738)	7.217 "
9.	1010.15 (737)	7.022 "
10.	971.15 (698)	" "
11.	" "	7.423 "
12.	970.15 (697)	7.217 "
13.	927.15 (654)	7.423 "
14.	" "	7.641 "
15.	926.15 (653)	" "
16.	873.15 (600)	7.641 "
17.	871.15 (598)	8.119 "
18.	870.15 (597)	7.873 "
19.	837.15 (564)	7.423 "
20.	" "	7.873 "
21.	" "	" "
22.	793.15 (520)	7.641 "
23.	" "	8.119 "
24.	792.15 (519)	" "
25.	745.15 (472)	" "
26.	744.15 (471)	8.381 "
27.	" "	8.119 "
28.	700.15 (427)	" "
29.	699.15 (426)	8.381 "
30.	698.15 (425)	8.119 "
31.	651.15 (378)	" "
32.	647.15 (374)	8.660 "
33.	646.15 (373)	" "
34.	596.15 (323)	8.381 "
35.	595.15 (322)	8.119 "

TABLE II - A (continued)

RAW THERMAL DIFFUSIVITY DATA - ALLOY B

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
36.	595.15 (322)	8.660×10^{-6}
37.	551.15 (278)	8.959 "
38.	" "	8.381 "
39.	" "	8.660 "
40.	517.15 (244)	8.119 "
41.	515.15 (242)	9.279 "
42.	513.15 (240)	" "

TABLE III - A

RAW THERMAL DIFFUSIVITY DATA - ALLOY C

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
1.	1079.15 (806)	7.097 x 10^{-6}
2.	" "	" "
3.	" "	7.514 "
4.	1053.15 (780)	7.300 "
5.	" "	7.514 "
6.	1052.15 (779)	7.742 "
7.	1012.15 (739)	" "
8.	" "	7.514 "
9.	" "	7.984 "
10.	963.15 (690)	7.742 "
11.	961.15 (688)	7.984 "
12.	958.15 (685)	" "
13.	919.15 (646)	" "
14.	917.15 (644)	" "
15.	916.15 (643)	" "
16.	882.15 (609)	8.242 "
17.	880.15 (607)	8.516 "
18.	878.15 (605)	7.984 "
19.	840.15 (567)	8.242 "
20.	838.15 (565)	7.984 "
21.	" "	" "
22.	797.15 (524)	8.516 "
23.	" "	7.984 "
24.	" "	8.242 "
25.	747.15 (474)	" "
26.	" "	7.984 "
27.	746.15 (473)	8.516 "
28.	697.15 (424)	" "
29.	696.15 (423)	" "
30.	695.15 (422)	" "
31.	645.15 (372)	8.242 "
32.	644.15 (371)	8.516 "
33.	" "	9.125 "
34.	597.15 (324)	8.516 "
35.	" "	8.810 "

TABLE III - A (continued)

RAW THERMAL DIFFUSIVITY DATA - ALLOY C

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
36.	596.15 (323)	8.516×10^{-6}
37.	552.15 (279)	8.810 "
38.	551.15 (278)	9.125 "
39.	550.15 (277)	" "
40.	512.15 (239)	8.242 "
41.	511.15 (238)	9.125 "
42.	510.15 (237)	9.827 "

TABLE IV - A

RAW THERMAL DIFFUSIVITY DATA - ALLOY D

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
1.	1070.15 (797)	7.641×10^{-6}
2.	" "	7.873 "
3.	" "	7.641 "
4.	1055.15 (782)	8.119 "
5.	" "	7.873 "
6.	" "	8.381 "
7.	1012.15 (739)	8.119 "
8.	1011.15 (738)	" "
9.	" "	" "
10.	970.15 (697)	7.641 "
11.	" "	8.119 "
12.	969.15 (696)	" "
13.	926.15 (653)	8.381 "
14.	" "	8.119 "
15.	925.15 (652)	" "
16.	880.15 (607)	" "
17.	879.15 (606)	" "
18.	878.15 (605)	" "
19.	838.15 (565)	8.381 "
20.	837.15 (564)	8.119 "
21.	" "	8.381 "
22.	788.15 (515)	" "
23.	787.15 (514)	8.660 "
24.	786.15 (513)	8.381 "
25.	742.15 (469)	8.660 "
26.	" "	8.381 "
27.	" "	8.660 "
28.	697.15 (424)	" "
29.	696.15 (423)	" "
30.	695.15 (422)	8.959 "
31.	651.15 (378)	8.660 "
32.	" "	8.959 "
33.	650.15 (377)	8.660 "
34.	601.15 (328)	8.959 "
35.	" "	9.279 "

TABLE IV - A (continued)

RAW THERMAL DIFFUSIVITY DATA - ALLOY D

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
36.	599.15 (326)	9.279×10^{-6}
37.	552.15 (279)	" "
38.	" "	" "
39.	" "	" "
40.	511.15 (238)	" "
41.	506.15 (233)	" "
42.	504.15 (231)	" "

TABLE V - A

RAW THERMAL DIFFUSIVITY DATA - ALLOY E

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
1.	1077.15 (804)	7.587×10^{-6}
2.	1076.15 (803)	6.744 "
3.	" "	7.587 "
4.	1055.15 (782)	8.670 "
5.	" "	" "
6.	1054.15 (781)	7.587 "
7.	1015.15 (742)	7.831 "
8.	" "	8.092 "
9.	1013.15 (740)	7.831 "
10.	972.15 (699)	8.371 "
11.	971.15 (698)	" "
12.	970.15 (697)	7.831 "
13.	924.15 (651)	8.371 "
14.	" "	" "
15.	923.15 (650)	8.670 "
16.	884.15 (611)	8.371 "
17.	" "	8.670 "
18.	883.15 (610)	8.371 "
19.	842.15 (569)	8.670 "
20.	" "	" "
21.	838.15 (565)	8.371 "
22.	788.15 (515)	" "
23.	" "	8.670 "
24.	787.15 (514)	" "
25.	745.15 (472)	" "
26.	" "	8.991 "
27.	744.15 (471)	8.670 "
28.	697.15 (424)	" "
29.	" "	8.991 "
30.	" "	8.670 "
31.	645.15 (372)	8.991 "
32.	" "	" "
33.	644.15 (371)	" "
34.	599.15 (326)	" "
35.	598.15 (325)	" "

TABLE V - A (continued)

RAW THERMAL DIFFUSIVITY DATA - ALLOY E

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
36.	596.15 (323)	8.991×10^{-6}
37.	545.15 (272)	8.670 "
38.	" "	" "
39.	544.15 (271)	9.337 "
40.	509.15 (236)	8.670 "
41.	" "	9.337 "
42.	506.15 (233)	" "

TABLE VI - A

RAW THERMAL DIFFUSIVITY DATA - ALLOY F

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
1.	1084.15 (811)	7.641 x 10^{-6}
2.	1082.15 (809)	7.217 "
3.	1080.15 (807)	7.641 "
4.	1054.15 (781)	7.423 "
5.	" "	8.119 "
6.	" "	7.423 "
7.	1014.15 (741)	7.641 "
8.	" "	7.217 "
9.	" "	" "
10.	974.15 (701)	7.641 "
11.	" "	7.423 "
12.	" "	8.660 "
13.	929.15 (656)	7.423 "
14.	" "	" "
15.	" "	" "
16.	884.15 (611)	7.873 "
17.	" "	" "
18.	883.15 (610)	7.217 "
19.	842.15 (569)	7.423 "
20.	" "	7.641 "
21.	841.15 (568)	7.423 "
22.	789.15 (516)	" "
23.	" "	7.641 "
24.	788.15 (515)	8.119 "
25.	744.15 (471)	7.641 "
26.	743.15 (470)	8.119 "
27.	742.15 (469)	7.873 "
28.	699.15 (426)	8.119 "
29.	" "	" "
30.	" "	8.381 "
31.	650.15 (377)	8.119 "
32.	" "	8.381 "
33.	649.15 (376)	7.873 "
34.	596.15 (323)	8.119 "
35.	" "	" "

TABLE VI - A (continued)

RAW THERMAL DIFFUSIVITY DATA - ALLOY F

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
36.	596.15 (323)	8.119×10^{-6}
37.	554.15 (281)	" "
38.	553.15 (280)	8.660 "
39.	552.15 (279)	" "
40.	505.15 (232)	8.959 "
41.	504.15 (231)	8.119 "
42.	502.15 (229)	" "

TABLE VII - A

RAW THERMAL DIFFUSIVITY DATA - ALLOY G

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
1.	1071.15 (798)	8.119×10^{-6}
2.	1070.15 (797)	" "
3.	" "	" "
4.	1055.15 (782)	" "
5.	" "	" "
6.	" "	" "
7.	1015.15 (742)	" "
8.	" "	" "
9.	1014.15 (741)	" "
10.	970.15 (697)	" "
11.	" "	" "
12.	969.15 (696)	" "
13.	926.15 (653)	" "
14.	925.15 (652)	" "
15.	" "	" "
16.	881.15 (608)	" "
17.	" "	" "
18.	" "	" "
19.	839.15 (566)	" "
20.	" "	8.381 "
21.	838.15 (565)	" "
22.	792.15 (519)	8.660 "
23.	" "	" "
24.	791.15 (518)	" "
25.	745.15 (472)	8.959 "
26.	" "	" "
27.	744.15 (471)	8.381 "
28.	699.15 (426)	9.279 "
29.	697.15 (424)	8.959 "
30.	695.15 (422)	9.279 "
31.	652.15 (379)	8.959 "
32.	651.15 (378)	" "
33.	650.15 (377)	9.279 "
34.	596.15 (323)	" "
35.	595.15 (322)	" "

TABLE VII - A (continued)

RAW THERMAL DIFFUSIVITY DATA - ALLOY G

DATA POINT	TEMPERATURE °K (°C)	T.D. m^2/sec
36.	595.15 (322)	9.279×10^{-6}
37.	552.15 (279)	" "
38.	551.15 (278)	" "
39.	550.15 (277)	" "
40.	510.15 (237)	9.622 "
41.	506.15 (233)	9.992 "
42.	503.15 (230)	9.279 "

APPENDIX

B

TABLE I - B

PERFORMANCE CHARACTERIZATION DATA - REPITITION ONE

All cuts continuous, work material = 1045 HRS, feed = .795 mm per rev. (.0313 ipr), depth = 2.54 mm (.100 in.), and all wear measurements are made after 9 minutes.

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW μm(mils)	NW μm(mils)
A	1	30.48(100)	1	30.5(1.2)	58.4(2.3)
"	"	"	2	22.9(0.9)	50.8(2.0)
"	"	"	3	22.9(0.9)	50.8(2.0)
"	"	"	4	25.4(1.0)	50.8(2.0)
"	"	"	5	22.9(0.9)	55.4(2.2)
"	"	"	6	25.4(1.0)	53.3(2.1)
A	2	60.96(200)	1	63.5(2.5)	91.4(3.6)
"	"	"	2	53.3(2.1)	94.0(3.7)
"	"	"	3	50.8(2.0)	88.9(3.5)
"	"	"	4	53.3(2.1)	88.9(3.5)
"	"	"	5	50.8(2.0)	91.4(3.6)
"	"	"	6	50.8(2.0)	91.4(3.6)
A	3	121.92(400)	1	180.3(7.1)	645.2(25.4)
"	"	"	2	177.8(7.0)	627.4(24.7)
"	"	"	3	165.1(6.5)	622.3(24.5)
"	"	"	4	172.1(6.8)	662.9(26.1)
"	"	"	5	177.8(7.0)	612.1(24.1)
"	"	"	6	167.6(6.6)	622.3(24.5)
B	1	30.48(100)	1	30.5(1.2)	81.3(3.2)
"	"	"	2	25.4(1.0)	86.4(3.4)
"	"	"	3	33.0(1.3)	78.7(3.1)
"	"	"	4	30.5(1.2)	81.3(3.2)
"	"	"	5	30.5(1.2)	86.4(3.4)
"	"	"	6	33.0(1.3)	83.8(3.3)
B	2	60.96(200)	1	96.5(3.5)	124.5(4.9)
"	"	"	2	81.3(3.2)	114.3(4.5)
"	"	"	3	81.3(3.2)	124.5(4.9)
"	"	"	4	78.7(3.1)	119.4(4.7)
"	"	"	5	81.3(3.2)	121.9(4.8)
"	"	"	6	78.7(3.1)	121.9(4.8)

TABLE I - B (continued)

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW µm(mils)	NW µm(mils)
B	3	121.92(400)	1	241.3(9.5)	777.2(30.6)
"	"	"	2	271.8(10.7)	787.4(31.0)
"	"	"	3	243.8(9.6)	734.1(28.9)
"	"	"	4	251.5(9.9)	749.3(29.5)
"	"	"	5	238.8(9.4)	767.1(30.2)
"	"	"	6	243.8(9.6)	746.8(29.4)
C	1	30.48(100)	1	40.6(1.6)	73.7(2.9)
"	"	"	2	40.6(1.6)	55.9(2.2)
"	"	"	3	45.7(1.8)	58.4(2.3)
"	"	"	4	40.6(1.6)	53.3(2.1)
"	"	"	5	48.3(1.9)	61.0(2.4)
"	"	"	6	38.1(1.5)	55.9(2.2)
C	2	60.96(200)	1	101.6(4.0)	129.5(5.1)
"	"	"	2	94.0(3.7)	144.8(5.7)
"	"	"	3	88.9(3.5)	144.8(5.7)
"	"	"	4	94.0(3.7)	134.6(5.3)
"	"	"	5	99.1(3.9)	147.3(5.8)
"	"	"	6	99.1(3.9)	144.8(5.7)
C	3	121.92(400)	1	266.7(10.5)	723.9(28.5)
"	"	"	2	307.3(12.1)	706.1(27.8)
"	"	"	3	284.5(11.2)	749.3(29.5)
"	"	"	4	297.2(11.7)	726.4(28.6)
"	"	"	5	279.4(11.0)	736.6(29.0)
"	"	"	6	274.3(10.8)	708.7(27.9)
D	1	30.48(100)	1	66.0(2.6)	86.4(3.4)
"	"	"	2	55.9(2.2)	78.7(3.1)
"	"	"	3	63.5(2.5)	81.3(3.2)
"	"	"	4	63.5(2.5)	86.4(3.4)
"	"	"	5	61.0(2.4)	78.7(3.1)
"	"	"	6	63.5(2.5)	78.7(3.1)
D	2	60.96(200)	1	71.1(2.8)	99.1(3.9)
"	"	"	2	63.5(2.5)	86.4(3.4)
"	"	"	3	58.4(2.3)	96.5(3.8)
"	"	"	4	63.5(2.5)	91.4(3.6)
"	"	"	5	61.0(2.4)	91.4(3.6)
"	"	"	6	61.0(2.4)	96.5(3.8)

TABLE I - B (continued)

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW µm(mils)	NW µm(mils)
D	3	121.92(400)	1	279.4(11.0)	1198.9(47.2)
"	"	"	2	271.8(10.7)	1104.9(43.5)
"	"	"	3	289.6(11.4)	1188.7(46.8)
"	"	"	4	287.0(11.3)	1145.5(45.1)
"	"	"	5	281.9(11.1)	1191.3(46.9)
"	"	"	6	287.0(11.3)	1193.8(47.0)
E	1	30.48(100)	1	35.6(1.4)	50.8(2.0)
"	"	"	2	30.5(1.2)	50.8(2.0)
"	"	"	3	27.9(1.1)	45.7(1.8)
"	"	"	4	25.4(1.0)	43.2(1.7)
"	"	"	5	30.5(1.2)	50.8(2.0)
"	"	"	6	25.4(1.0)	48.3(1.9)
E	2	60.96(200)	1	43.2(1.7)	66.0(2.6)
"	"	"	2	48.3(1.9)	63.5(2.5)
"	"	"	3	43.2(1.7)	61.0(2.4)
"	"	"	4	45.7(1.8)	66.0(2.6)
"	"	"	5	48.3(1.9)	61.0(2.4)
"	"	"	6	43.2(1.7)	58.4(2.3)
E	3	121.92(400)	1	248.9(9.8)	629.9(24.8)
"	"	"	2	223.5(8.8)	657.9(25.9)
"	"	"	3	274.3(10.8)	586.7(23.1)
"	"	"	4	254.0(10.0)	635.0(25.0)
"	"	"	5	241.3(9.5)	589.3(23.2)
"	"	"	6	259.1(10.2)	612.1(24.1)
F	1	30.48(100)	1	38.1(1.5)	78.7(3.1)
"	"	"	2	38.1(1.5)	81.3(3.2)
"	"	"	3	33.0(1.3)	71.1(2.8)
"	"	"	4	30.5(1.2)	71.1(2.8)
"	"	"	5	38.1(1.5)	78.7(3.1)
"	"	"	6	33.0(1.3)	68.6(2.7)
F	2	60.96(200)	1	81.3(3.2)	101.6(4.0)
"	"	"	2	73.7(2.9)	88.9(3.5)
"	"	"	3	68.6(2.7)	86.4(3.4)
"	"	"	4	71.1(2.8)	83.8(3.3)
"	"	"	5	76.2(3.0)	86.4(3.4)
"	"	"	6	71.1(2.8)	86.4(3.4)

TABLE I - B (continued)

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW µm(mils)	NW µm(mils)
F	3	121.92(400)	1	309.9(12.2)	975.4(38.4)
"	"	"	2	279.4(11.0)	886.5(34.9)
"	"	"	3	312.4(12.3)	970.3(38.2)
"	"	"	4	302.3(11.9)	942.3(37.1)
"	"	"	5	304.8(12.0)	962.7(37.9)
"	"	"	6	312.4(12.3)	965.2(38.0)
G	1	30.48(100)	1	35.6(1.4)	50.8(2.0)
"	"	"	2	35.6(1.4)	58.4(2.3)
"	"	"	3	33.0(1.3)	58.4(2.3)
"	"	"	4	40.6(1.6)	45.7(1.8)
"	"	"	5	43.2(1.7)	55.9(2.2)
"	"	"	6	33.0(1.3)	55.9(2.2)
G	2	60.96(200)	1	63.5(2.5)	76.2(3.0)
"	"	"	2	58.4(2.3)	78.7(3.1)
"	"	"	3	58.4(2.3)	81.3(3.2)
"	"	"	4	63.5(2.5)	78.7(3.1)
"	"	"	5	61.0(2.4)	81.3(3.2)
"	"	"	6	58.4(2.3)	81.3(3.2)
G	3	121.92(400)	1	236.2(9.3)	599.4(23.6)
"	"	"	2	259.1(10.2)	723.9(28.5)
"	"	"	3	223.5(8.8)	825.5(32.5)
"	"	"	4	208.3(8.2)	612.1(24.1)
"	"	"	5	231.1(9.1)	655.3(25.8)
"	"	"	6	223.5(8.8)	589.3(23.2)

TABLE II - B

PERFORMANCE CHARACTERIZATION DATA - REPITITION TWO

All cuts continuous, work material = 1045 HRS, feed = .795 mm per rev. (.0313 ipr), depth = 2.54 mm (.100 in.), and all wear measurements are made after 9 minutes.

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW µm(mils)	NW µm(mils)
A	1	30.48(100)	1	33.0(1.3)	53.4(2.1)
"	"	"	2	30.5(1.2)	73.7(2.9)
"	"	"	3	25.4(1.0)	66.1(2.6)
"	"	"	4	27.9(1.1)	76.2(3.0)
"	"	"	5	25.4(1.0)	63.5(2.5)
"	"	"	6	22.9(0.9)	66.1(2.6)
A	2	60.96(200)	1	66.1(2.6)	101.6(4.0)
"	"	"	2	58.4(2.3)	119.4(4.7)
"	"	"	3	55.9(2.2)	109.2(4.3)
"	"	"	4	61.0(2.4)	104.2(4.1)
"	"	"	5	55.9(2.2)	114.3(4.5)
"	"	"	6	58.4(2.3)	111.8(4.4)
A	3	121.92(400)	1	165.1(6.5)	622.4(24.5)
"	"	"	2	180.4(7.1)	658.0(25.9)
"	"	"	3	182.9(7.2)	663.1(26.1)
"	"	"	4	175.3(6.9)	647.8(25.5)
"	"	"	5	172.8(6.8)	632.6(24.9)
"	"	"	6	182.9(7.2)	658.0(25.9)
B	1	30.48(100)	1	30.5(1.2)	104.2(4.1)
"	"	"	2	25.4(1.0)	88.9(3.5)
"	"	"	3	27.9(1.1)	83.8(3.3)
"	"	"	4	30.5(1.2)	91.5(3.6)
"	"	"	5	27.9(1.1)	88.9(3.5)
"	"	"	6	30.5(1.2)	94.0(3.7)
B	2	60.96(200)	1	91.5(3.6)	144.8(5.7)
"	"	"	2	81.3(3.2)	157.2(6.2)
"	"	"	3	78.8(3.1)	152.4(6.0)
"	"	"	4	86.4(3.4)	157.2(6.2)
"	"	"	5	78.8(3.1)	162.6(6.4)
"	"	"	6	81.3(3.2)	160.1(6.3)

TABLE II - B (continued)

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW μm(mils)	NW μm(mils)
B	3	121.92(400)	1	221.0(8.7)	630.0(24.8)
"	"	"	2	193.1(7.6)	675.8(26.6)
"	"	"	3	213.4(8.4)	655.5(25.8)
"	"	"	4	215.9(8.5)	665.6(26.2)
"	"	"	5	208.3(8.2)	673.2(26.5)
"	"	"	6	218.5(8.6)	632.6(24.9)
C	1	30.48(100)	1	45.7(1.8)	83.8(3.3)
"	"	"	2	50.8(2.0)	63.5(2.5)
"	"	"	3	43.2(1.7)	63.5(2.5)
"	"	"	4	48.3(1.9)	71.1(2.8)
"	"	"	5	43.2(1.7)	78.8(3.1)
"	"	"	6	43.2(1.7)	63.5(2.5)
C	2	60.96(200)	1	99.1(3.9)	109.2(4.3)
"	"	"	2	94.0(3.7)	96.5(3.8)
"	"	"	3	99.1(3.9)	101.6(4.0)
"	"	"	4	91.5(3.6)	116.9(4.6)
"	"	"	5	99.1(3.9)	114.3(4.5)
"	"	"	6	101.6(4.0)	114.3(4.5)
C	3	121.92(400)	1	302.3(11.9)	777.4(30.6)
"	"	"	2	330.3(13.0)	787.6(31.0)
"	"	"	3	325.2(12.8)	792.6(31.2)
"	"	"	4	304.9(12.0)	774.9(30.5)
"	"	"	5	312.5(12.3)	759.6(29.9)
"	"	"	6	320.1(12.6)	785.0(30.9)
D	1	30.48(100)	1	61.0(2.4)	86.4(3.4)
"	"	"	2	48.3(1.9)	61.0(2.4)
"	"	"	3	50.8(2.0)	68.6(2.7)
"	"	"	4	45.7(1.8)	76.2(3.0)
"	"	"	5	48.3(1.9)	71.1(2.8)
"	"	"	6	53.4(2.1)	73.7(2.9)
D	2	60.96(200)	1	73.7(2.9)	88.9(3.5)
"	"	"	2	63.5(2.5)	78.8(3.1)
"	"	"	3	71.1(2.8)	76.2(3.0)
"	"	"	4	73.7(2.9)	81.3(3.2)
"	"	"	5	68.6(2.7)	81.3(3.2)
"	"	"	6	71.1(2.8)	78.8(3.1)

TABLE II - B (continued)

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW μm(mils)	NW μm(mils)
D	3	121.92(400)	1	254.1(10.0)	876.5(34.5)
"	"	"	2	241.3(9.5)	932.4(36.7)
"	"	"	3	238.8(9.4)	945.1(37.2)
"	"	"	4	249.0(9.8)	912.0(35.9)
"	"	"	5	241.3(9.5)	940.0(37.0)
"	"	"	6	243.9(9.6)	942.5(37.1)
E	1	30.48(100)	1	30.5(1.2)	48.3(1.9)
"	"	"	2	25.4(1.0)	35.6(1.4)
"	"	"	3	22.9(0.9)	45.7(1.8)
"	"	"	4	20.3(0.8)	40.6(1.6)
"	"	"	5	25.4(1.0)	50.8(2.0)
"	"	"	6	30.5(1.2)	48.3(1.9)
E	2	60.96(200)	1	58.4(2.3)	86.4(3.4)
"	"	"	2	63.5(2.5)	88.9(3.5)
"	"	"	3	61.0(2.4)	83.8(3.3)
"	"	"	4	66.0(2.6)	76.2(3.0)
"	"	"	5	63.5(2.5)	86.4(3.4)
"	"	"	6	63.5(2.5)	83.8(3.3)
E	3	121.92(400)	1	243.8(9.6)	820.4(32.3)
"	"	"	2	274.3(10.8)	845.8(33.3)
"	"	"	3	259.1(10.2)	861.1(33.9)
"	"	"	4	251.5(9.9)	828.0(32.6)
"	"	"	5	264.2(10.4)	835.7(32.9)
"	"	"	6	256.5(10.1)	840.7(33.1)
F	1	30.48(100)	1	25.4(1.0)	58.4(2.3)
"	"	"	2	33.0(1.3)	50.8(2.0)
"	"	"	3	30.5(1.2)	61.0(2.4)
"	"	"	4	25.4(1.0)	71.1(2.8)
"	"	"	5	27.9(1.1)	63.5(2.5)
"	"	"	6	30.5(1.2)	71.1(2.8)
F	2	60.96(200)	1	73.7(2.9)	94.0(3.7)
"	"	"	2	55.9(2.2)	76.2(3.0)
"	"	"	3	63.5(2.5)	73.7(2.9)
"	"	"	4	61.0(2.4)	83.8(3.3)
"	"	"	5	58.4(2.3)	78.7(3.1)
"	"	"	6	71.1(2.8)	76.2(3.0)

TABLE II - B (continued)

ALLOY CODE	CORNER NUMBER	SPEED SMPM(SFPM)	READING NUMBER	FW µm(mils)	NW µm(mils)
F	3	121.92(400)	1	373.4(14.7)	1153.2(45.4)
"	"	"	2	271.8(10.7)	1056.6(41.6)
"	"	"	3	274.3(10.8)	1112.5(43.8)
"	"	"	4	274.3(10.8)	1087.1(42.8)
"	"	"	5	281.9(11.1)	1125.3(44.3)
"	"	"	6	271.8(10.7)	1122.7(44.2)
G	1	30.48(100)	1	33.0(1.3)	61.0(2.4)
"	"	"	2	35.6(1.4)	61.0(2.4)
"	"	"	3	35.6(1.4)	58.4(2.3)
"	"	"	4	35.6(1.4)	58.4(2.3)
"	"	"	5	30.5(1.2)	55.9(2.2)
"	"	"	6	33.0(1.3)	61.0(2.4)
G	2	60.96(200)	1	53.3(2.1)	71.1(2.8)
"	"	"	2	45.7(1.8)	73.7(2.9)
"	"	"	3	50.8(2.0)	71.1(2.8)
"	"	"	4	48.3(1.9)	73.7(2.9)
"	"	"	5	53.3(2.1)	71.1(2.8)
"	"	"	6	53.3(2.1)	66.0(2.6)
G	3	121.92(400)	1	205.7(8.1)	660.4(26.0)
"	"	"	2	203.2(8.0)	703.6(27.7)
"	"	"	3	210.8(8.3)	716.3(28.2)
"	"	"	4	198.1(7.8)	706.1(27.8)
"	"	"	5	198.1(7.8)	678.2(26.7)
"	"	"	6	203.2(8.0)	708.7(27.9)

"Vita"

The author was born on June 22, 1952, in Lancaster, Pennsylvania, the eldest of four sons of Joseph and Ruth Ann Colgrove. He moved to Clarks Summit, Pennsylvania in August of 1966, and then to Basking Ridge, New Jersey in August of 1969. He graduated from Ridge High School in June, 1970, and proceeded to enter Lehigh University in the Fall of 1970. While at Lehigh, he became a member, and was a past Vice-President of Sigma Nu Fraternity. In May, 1974 he received a Bachelor of Science Degree in Industrial Engineering. At that time, he was awarded a Teaching Assistantship in Industrial Engineering from Lehigh University, and thus he returned in the Fall of 1974 for graduate work. The author holds the rank of Eagle Scout BSA, he is currently a member and Vice-President of AIIE Lehigh Valley Student Chapter, and a member of SME. His parents currently reside in Leola, Pennsylvania, where his father is employed by Radio Corporation of America as Vice-President and General Manager of the Color Picture Tube Division, based in Lancaster, Pennsylvania.